Comparison of Grainflow Activity on Earth and Mars
Utilising 3D Microscale Airflow Modelling

By

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Summary

Dune migration is accomplished by individual grainflows that redistribute sediment downslope, locally advancing the slipface. As rainfall and grain saltation over the dune brink restores the slope, subsequent grainflows may take place. The frequency in which grainflows occur is dependent on sediment availability, sediment flux, and the wind regime of the aeolian environment. Slipface dynamics have been the focus of many terrestrial aeolian studies aiming to better understand the mechanisms of dune migration using a variety of approaches including wind tunnel experiments, airflow modelling, and field observation. Until recently, the study of slipface dynamics was confined to Earth due to lack of in situ observations on Mars. In December 2015, the Mars Science Laboratory Curiosity Rover visited a martian dune and collected data on the local wind regime, aeolian sediment characteristics, and high resolution images of the dune slipface. This new data opened a new avenue for aeolian research, making it possible to directly compare terrestrial and martian dune slipface dynamics.

This study uses terrestrial field observations from the Maspalomas dune field in Gran Canaria, Spain as a Mars analog to the grainflows imaged by Curiosity on Mars on the Namib dune. The Earth-based research is comprised of video documentation of the dynamics of grainflows and a series of ground-based laser scans that captured the morphometric characteristics of grainflows, including morphology, thickness, and area. These observations are compared to the martian slipface to interpret the grainflow activity preserved on the dune. These interpretations augmented by Computation Fluid Dynamics Modelling at the dune-scale to investigate the influence of the local martian wind regime on aeolian features and sediment transport.

The results demonstrate that similar aeolian slipface processes are operating on Earth and Mars. Due to Mars’ low density atmosphere, wind speeds must be significantly greater to initiate grain movement and therefore, the Namib dune is likely subject to short-term intermittent seasonal aeolian activity. Modelling results suggest that there are limited times during the martian day and year when sand grains are mobilised and slipface advancement may largely be confined to the spring season.
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>Model Constant</td>
</tr>
<tr>
<td>DTM</td>
<td>Digital Terrain Model</td>
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<td>HiRISE</td>
<td>High Resolution Imaging Science Experiment</td>
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<td>$k$</td>
<td>Turbulent Kinetic Energy</td>
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<td>LMST</td>
<td>Local Mars Solar Time</td>
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<tr>
<td>MSL</td>
<td>Mars Science Laboratory</td>
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<tr>
<td>MRAMS</td>
<td>Mars Regional Atmospheric Modelling System</td>
</tr>
<tr>
<td>MRO</td>
<td>Mars Reconnaissance Orbiter</td>
</tr>
<tr>
<td>MSL</td>
<td>Mars Science Laboratory</td>
</tr>
<tr>
<td>MY</td>
<td>Mars Year</td>
</tr>
<tr>
<td>OpenFOAM</td>
<td>Open Field Operation and Manipulation</td>
</tr>
<tr>
<td>PDS</td>
<td>Planetary Data System</td>
</tr>
<tr>
<td>REMS</td>
<td>Rover Environmental Monitoring Station</td>
</tr>
<tr>
<td>RTK GPS</td>
<td>Real Time Kinematic Global Positioning System</td>
</tr>
<tr>
<td>STL</td>
<td>StereoLithography</td>
</tr>
<tr>
<td>TKE</td>
<td>Turbulent Kinetic Energy</td>
</tr>
<tr>
<td>TLS</td>
<td>Terrestrial Laser Scanner</td>
</tr>
<tr>
<td>$u_*$</td>
<td>Shear Velocity</td>
</tr>
<tr>
<td>$u$</td>
<td>Streamwise velocity</td>
</tr>
<tr>
<td>WRF</td>
<td>Weather Research and Forecasting</td>
</tr>
<tr>
<td>$z_0$</td>
<td>Aerodynamic roughness length</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Turbulent dissipation</td>
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<tr>
<td>$\kappa$</td>
<td>von Kármán coefficient</td>
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CHAPTER 1

Introduction
1.1 Background

In the absence of liquid water on Mars, aeolian processes are the primary geomorphic agent acting on the planet surface today (Sagan et al., 1973). With the arrival of Mariner 9 spacecraft in 1971, a variety of aeolian features were revealed, many of which are the result of long-term geologic processes (Cutts and Smith, 1973; Masursky, 1973). Dune fields, in particular, are ubiquitous on the surface of Mars being present at all latitudes and environments (Thomas, 1982). Aeolian bedforms were initially discovered in Mariner 9 images (Fig. 1a; McCauley et al., 1972; Sagan et al., 1972; Cutts and Smith, 1973) having a resolution between 0.1 and 1 km/pixel (McCauley, 1973). Mars spacecraft image resolution today now exceeds that of terrestrial satellites, having a pixel scale of 25 cm (Fig. 1b, c; Bridges et al., 2007). The High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter is capable of resolving secondary ripples on dunes and since its arrival to Mars in 2006, the accumulation of repeat coverage of certain locations on Mars has enabled estimates of dune and ripple migration (e.g. Silvestro et al., 2010; Chojnacki et al., 2011; Bridges et al., 2011; Hansen et al., 2011; Silvestro et al., 2011; Bridges et al., 2012). In addition, the Mars Science Laboratory Curiosity rover visited an active dune within the Bagnold dune field in Gale Crater on Mars in 2014, revealing for the first time morphologic details of a dune slipface not resolved by HiRISE imagery. These images provided the means to directly compare terrestrial slipface dynamics to martian aeolian processes and created a new avenue of research into the morphodynamics of dune fields on Mars (e.g. Bridges et al., 2017; Ewing et al., 2017).
Before HiRISE images, it was unclear if aeolian deposits were actively moving because the wind speeds required to overcome fluid threshold friction and initiate grain saltation in the low-density atmosphere were rare according to wind tunnel experiments and atmospheric models (Arvidson et al., 1983; Haberle et al., 2003). More recently, a numerical model predicted that the behavior of a sand grain, mobilised sporadically, behaves differently under terrestrial and martian conditions (Sullivan and Kok, 2017). High velocity gusts of wind on Mars may mobilise individual grains which

Figure 1. The Proctor Crater dune field where the first dunes were identified on Mars (A) by McCauley et al. (1972) using a Mariner 9 image (NSSDC ID: PSPG-00235 71-051A-04c) compared to the current day image resolution of HiRISE (ESP_024291_1320) with a resolution of 25cm/pixel (B and C). Red box represents the extent of box C, where boulders and ripples and light-tones ridges are resolved.
develop self-sustaining saltation trajectories (Kok, 2010a, 2010b; Yizhaq et al., 2014). Upon impact, these grains transfer energy to the surface, splashing other grains which results in a hysteresis effect whereupon an increased amount of grains are set in motion and propagate grain saltation downwind (Kok, 2010a; Kok et al., 2012; Sullivan and Kok, 2017). The lower martian gravity allows grains to be airborne for longer, compared to terrestrial conditions, and during this time, the grain is accelerated by surface winds which counteract the effect of the lower martian atmospheric density (Sullivan and Kok, 2017). This results in a greater impact energy than similarly-sized sand grains of Earth and can produce sustained saltation at low wind speeds below the fluid threshold (Kok, 2010a; Kok et al., 2012; Sullivan and Kok, 2017).

Unfortunately, while the Curiosity rover visited the Bagnold dune field, it did not capture any significant aeolian modification during its stay. A comparison of images between martian days of a single dune showed that sediment movement was limited to “scrambling”, where only a few sand grains moved with an inconsistent direction of transport (Bridges et al., 2017). In the absence of continued in situ observation and the lack of documentation of active aeolian processes, a Mars analog is needed to infer details about the dynamics of bulk sediment transport. In addition, more knowledge is needed about the local wind regime which drives sediment transport. Airflow is complex and highly sensitive to small-scale local topography and can significantly impact sediment transport on dunes. Therefore, an understanding for the local wind regime is essential for understanding how the dunes in the Bagnold dune field formed and how they continue to be influenced by the wind field.
To date, airflow patterns based on Curiosity wind data within Gale Crater have been explored primarily through the use of mesoscale models with a horizontal resolution between 400 and 500 m (e.g. Pla-Garcia et al., 2016; Rafkin et al., 2016; Newman et al., 2017; Bridges et al., 2017). Larger scale influences on the local wind regime within Gale Crater likely include a variety of factors such as seasonal planetary-scale circulation patterns, thermal tide, winds affected by large-scale topographic slopes, and the large amplitude mountain waves and turbulence generated by Mount Sharp, the central crater mound in which the Bagnold dune field surrounds (Fig. 2; Rafkin et al., 2016). Data from the Curiosity rover including, air temperature, ground temperature, pressure and wind direction and magnitude were compared to the Mars Regional Atmospheric Modelling System with good agreement, indicating that the mesoscale model is accurately simulating the major meteorological features of Gale Crater (Pla-Garcia et al., 2016). Similarly, the Mars Weather Research and Forecasting mesoscale model also had good agreement with the rover data (Newman et al., 2017) with only a couple discrepancies between the model predictions and measured wind data. Measured wind directions tended to have a more westerly and easterly component than the wind direction predicted by the model and the strength of daytime winds were approximately 2 – 4 m s$^{-1}$ weaker during simulations (Newman et al., 2017). These discrepancies are likely the cumulative result of the effects of small scale topography (<400 m) altering wind direction and magnitude.

To fully comprehend the forcing mechanisms that drive sediment transport and dune migration, a finer-scale airflow model is needed that can resolve the local
topography at the dune scale. With a finer-scale airflow model, the effects of topographic obstacles and wind speed-up factor on slopes (e.g. Lancaster, 1985; Neumann et al., 1997; Momiji et al., 2000; Sauermann et al., 2003; Parsons et al., 2004; Livingstone et al., 2007; Bo and Zheng, 2013) as well as the details of complex airflow patterns downwind from a dune such as flow detachment from the brink (Schatz and Herrmann, 2006; Delgado-Fernandez et al., 2013; Smyth et al., 2011, 2012, 2013), vortices (Jackson et al., 2011, 2013a, 2015), and eddies (Wiggs and Weaver, 2012) are resolved and constraints on sediment transport and dune migration can be established.
1.2 Research aims and objectives

The primary aim of the study was to examine grainflow formation mechanisms on Earth and investigate dune-scale wind flow variability using a combination of a terrestrial analog of a Mars dune and computational fluid dynamics modelling to better understand aeolian processes on Mars. More specifically the objectives were to:

- Collect data on the morphodynamics of grainflows on a desert dune using a combination of video recordings and a series of terrestrial-based high resolution laser scans.
- Compare terrestrial grainflow morphology, area, flow thickness, and volume to those imaged by Curiosity rover on the Namib dune in Gale Crater, Mars and use field data as an analog for the dynamics of martian grainflow.
- Investigate dune-scale airflow around the Namib dune on Mars using Curiosity Rover Environmental Monitoring Station data with a three-dimensional computational fluid dynamics model and relate the derived airflow patterns to ripple and grainflow formation.
- Constrain seasonal and diurnal periods of time favourable for grainflow activity and ripple migration and verify these periods of activity using satellite data.

To meet these objectives, a variety of analysis techniques, high resolution laser and leading edge microscale computer modelling approaches were employed. The details of grainflow formation, evolution, and physical characteristics were possible through
simultaneous video and laser scan coverage. Application of this field data to the grainflows on the Namib dune on Mars provided critical context for grainflow formation mechanisms in the absence of continued in situ observations during times of aeolian activity. Micro-scale computational fluid dynamics modelling provided a means to investigate the local forcing mechanisms that drive martian grainflow and ripple formation. Full details on the above techniques are provided in the following chapters.

1.3 Study sites

This research consists of two study sites including a Mars analog in the Maspalomas dune field, Gran Canaria, Spain, and the Bagnold dune field in Gale Crater, Mars.

1.3.1 Maspalomas Dune Field, Gran Canaria, Spain

The slipface of a large transverse dune with a height of 9.62 m in the central region of the Maspalomas dune field was used as a Mars analog for grainflow formation and dynamics. Observations were restricted to a 5 x 2 meter portion of the large slipface to ensure high quality data and sufficient detail for morphometric analysis. The dune field has a total area of about 4 km² and is comprised of primarily transverse dunes with a mixture of increasingly smaller transverse and barchanoid dune shapes to the east. The study site is located on the southern end of the Gran Canaria Island (Fig. 3) where data collection took place ca. 500 meters inland from the ocean at 27° 44’ 41.2” N 15°
The Maspalomas dunes are located in an arid climate, having less than 100 mm yr\(^{-1}\) precipitation (Marzol, 1987) with sparse vegetation and regular aeolian activity, thus making it a suitable field site for dune morphodynamic studies. Observations were collected during a single day on 8 December 2014 in the winter season when the
eastern and north eastern winds are strongest and have the most influence on dune migration (Hernandez et al., 2002; Jackson et al., 2013b; Hernandez et al., 2014). Meteorological data was retrieved from a weather station approximately 2.5 km southwest of the study site and recorded an average temperature of 21°C, humidity levels around 52%, and wind from ~55° (northeast) with an average wind velocity at 1 m height of 9.51 m s⁻¹ (±0.09 m s⁻¹) and a maximum gust speed of 23.14 m s⁻¹ on the day of data collection.

Sediments in the Maspalomas dune field are composed of a mixture of calcium carbonate/biogenic marine materials (Alcantara-Carrio, 1998; Hernandez et al., 2002) and phonolitic rocks weathered from the island volcanic deposits (Martinez, 1986) with an average grain size of 220 μm (Alacantara-Carrio, 1998). A small salt component was also found in the sand after sample splitting and a standard sieve analysis was completed using a series of nested sieves with quarter phi set. The salt comprised grain sizes less than 100 μm and was the most abundant in the interdune area.

1.3.2 Bagnold Dune Field, Gale Crater, Mars

Gale Crater has a diameter of approximately 150 km and is situated near the equator of Mars on the boundary of the smooth northern lowlands and the ancient southern cratered highlands (Fig. 4). The Bagnold dune field encircles the northern flank of the central mound of Gale Crater and a portion of the dune field was visited by the Mars Science Laboratory Curiosity rover in December 2015 (Fig. 2 and 4). The Bagnold
dunes are a mixture of linear and barchan dunes composed of sediments less than 250 μm with a few grains larger than 500 μm (Bridges et al., 2017; Elhmann et al., 2017). Aeolian sediment mineralogy is primarily basaltic in composition, with plagioclase, olivine and two Ca-Mg-Fe pyroxenes as the dominant crystalline phases (Achilles et al., 2017; Cousin et al., 2017; Elhmann et al., 2017; O’Connell-Cooper et al., 2017). One dune was observed in detail by the rover, known as the Namib dune (Fig. 5), which is the focus of this study. The Namib dune has an asymmetrical barchan

Figure 4. Location of Gale Crater on Mars as view looking toward the south (top) and the location of a portion of the Bagnold dune field with the landing site location and the path taken by Curiosity through the dune field (bottom). Image taken from http://www.sciencemag.org/news/2017/02/mars-rover-steps-hunt-molecular-signs-life
morphology, measuring 4 m in height and 77 m in length with a slipface slope ranging between 20° and 35° and an average of 27° (Ewing et al., 2017). The stoss slope of the Namib dune is covered in large ripples with ~1 m wavelengths and mantled by impact ripples that contour over and around the brink and downwind slopes of these large ripples (Ewing et al., 2017). The primary slipface of the Namib dune features a variety of preserved sedimentary processes including grainflow, grainfall, and large ripples and
impact ripples with grainflows dominating the apex of the curvature of the lee (Ewing et al., 2017).

1.4 Outline of thesis

Chapters 2, 3, 4, and 5 in this thesis comprise a series of journal articles that have either been published, are in press, or have been submitted for publication. The final chapter synthesizes the research contained in the thesis, highlighting the key findings and contributions of the study.


Chapter 3. Aeolian Slipface Dynamics and Grainflow Morphologies on Earth and Mars. Submitted to Icarus

Chapter 4. High Resolution Airflow Modelling Over the Namib Dune, Gale Crater, Mars: Seasonal Variations and Implications for Dune Dynamics.

Chapter 5. Bedform-Scale Modelling of Diurnal Airflow Patterns on Namib Dune, Gale Crater, Mars.

Chapter 6. Summary of findings and contributions.
References


Hansen, C. J. et al. (2011) Seasonal erosion and restoration of Mars northern polar dunes, Science, 331(6017), 575-578.


CHAPTER 2

Morphometric Analysis of Slipface Processes of an Aeolian Dune: Implications for Grainflow Dynamics

Sedimentology

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Abstract

Grainflows are an integral part of sand dune migration. They are a direct response to the local wind regime and reflect complex interactions between localised over-steepening of a dune slipface and complex turbulent airflow on the lee slope. Grainflows are primarily responsible for delivering sediment to the base of a dune thus driving slipface advancement; yet, there are few constraints on their morphological and spatial characteristics or the amount of sediment that is redistributed by these flows. Using a combination of high-resolution terrestrial laser scanning and video recordings, four distinct grainflow types are identified based on morphology and area on a dune slipface. Grainflow morphologies range from small, superficial flows to larger flows that affect greater portions of the slipface, moving significant amounts of sediment. Detailed field observations are presented of the dynamics of lee slopes, including measurements of the initiation location, thickness, magnitude and frequency statistics of grainflows as well as volume estimates of redistributed sediment for each grainflow observed. High-resolution laser scans enable accurate quantification of bulk sediment transfer from individual grainflows and can be used to study grainflows in a variety of environments. A categorization of grainflow morphologies is presented that links styles of flows with wind strength and direction, turbulent airflow, sediment deposition, and environment.

2.1 Introduction

Grainflows, or avalanching, on aeolian dunes is an essential process in dune migration. The migration of dunes is largely accomplished via a cycle involving the
occurrence of a grainflow that redistributes sediment downslope on the lee slope, advancing the slipface locally. Grainflow activity is followed by the restoration of the slope from rainfall deposition and grain saltation over the brink whereupon another grainflow may take place (e.g. Bagnold, 1941; Allen, 1970; Hunter, 1977; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1995; Kok et al., 2012). Grainflows have been the focus of many studies including in situ observations of active dunes, interpretations of flow signatures and paleoenvironments in aeolianites, wind tunnel experiments and numerical modelling approaches. Despite these studies, there is still a lack of knowledge regarding grainflow formation, initiation, magnitude, flow morphologies, and behavior under a variety of wind conditions and environments (e.g. Walker, 1999; Walker 2000; Cupp et al., 2005; Breton et al., 2008; Sutton et al., 2013; Nield et al., 2017). There is a need for additional field observations, wind tunnel experimentation, and numeric modelling over a wide range of aeolian settings and dune morphologies as well as a classification system of grainflows to begin constraining spatial, morphological, and dynamic characteristics of grainflows. This study presents the foundation of a classification system which can be used by future studies to describe grainflow attributes observed in the field or during wind tunnel experiments and can also be used to compare grainflow behavior between a variety of environments.

2.1.1 Grainflow Formation.

The frequency of grainflows is thought to be dependent on factors such as the depositional rate (correlated to wind velocity), and sediment characteristics or
environmental conditions which may affect grain movement or angle of repose (e.g. Allen, 1968; Allen, 1970; Sweet and Kocurek, 1990; McDonald and Anderson, 1992; McDonald and Anderson, 1995; Nickling et al., 2002; Cupp et al., 2005; Breton et al., 2008; Sutton, 2012; Sutton et al., 2013a,b; Pelletier et al., 2015; Nield et al., 2017).

However, the mechanism of formation and initiation of grainflows is more complex. Grainflows have been observed to be triggered by a localised over-steepening of the slipface slope near the dune brink where saltating grains are transported from the stoss slope on to the lee slope tens of centimetres below the brink (e.g. Allen, 1968; Allen, 1970; Borowka, 1979; Hunter, 1985; Anderson, 1988; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005; Kok et al., 2012; Sutton et al., 2013a,b). This process continues to form a bulge of sediment until it reaches the angle of initial yield (or exceeds the angle of repose of the sediment) and then fails. Failure occurs near the lower inflection point of the sediment bulge from which a tongue of sediment subsequently flows downslope (e.g. McDonald and Anderson, 1992; McDonald and Anderson, 1995; Tischer et al., 2001; Cupp et al., 2005; Dasgupta and Manna, 2011; Sutton, 2012; Sutton et al., 2013a,b; Nield et al., 2017). As sediment is removed, a scarp forms and simultaneously migrates upslope, spreading laterally (e.g. Hunter, 1977; Fryberger and Schenk, 1981). The resulting morphology is that of an alcove or zone of depletion just below the dune brink and a tongue of sediment or zone of accumulation directly downslope of the alcove (Sutton, 2012; Sutton et al., 2013a,b).

An alternative grainflow mechanism was described by Fryberger and Schenk (1981) from wind tunnel experiments. They characterised two mechanisms of grainflow
including scarp recession (originally described by Hunter (1977) and related to the formation of an alcove detailed above) and slump degeneration. Fryberger and Schenk (1981) observed that slump degeneration was the most common mechanism during their experiments. Each slump began as a series of tensional features near the top of the artificial slipface. The flow progressed with compressional features (folds) forming in places where the sediment slowed and overrode other parts of the flow. The resulting ‘slump sheet’ produced minor deformational structures in cross section suggesting cohesive sand, although the cause of cohesion in the dry sand was never discovered. Sutton et al. (2013b) applied the term slump degeneration to a small non-cohesive slab (100 – 400cm$^2$) which disintegrated after flowing a few centimetres downslope.

2.1.2 Grainflow Initiation

Breton et al. (2008) characterised two types of grainflows based on flow triggers during field observation. The first, was named primary flow and was observed to initiate by sediment accumulation on the slipface near the brink consistent with previous descriptions of localised slope over-steepening with the formation of an alcove and sediment tongue (Allen, 1968; Allen, 1970; Hunter, 1977; Borowka, 1979; Fryberger and Schenk, 1981; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1992; McDonald and Anderson, 1995; Tischer et al., 2001; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005; Dasgupta and Manna, 2011; Kok et al., 2012; Sutton, 2012; Sutton et al., 2013a,b, Nield et al., 2017). The second, referred to as a secondary flow, was thought to be initiated by disturbances on the slipface due to primary flows and
were generally smaller and occurred soon after primary flows. The secondary flows reported in that study are reminiscent of grainflows that occur midslope in ‘lock up zones’ on taller dunes (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996) where grainflows are unsuccessful in transporting sediment to the base of the slipface. Additionally, the upper-midslope is also known to be the location where finer, suspended particles from the sediment cloud launched from the dune brink accumulate, creating a potential secondary location for localised over-steepening and grainflow (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996; Nickling et al., 2002; Nield et al., 2017). However, the possible influence of a ‘lock up zone’ or suspended sediment settling mid slope and the occurrence of smaller grainflows was not made in Breton et al. (2008) potentially suggesting that destabilization from larger grainflows may be an additional grain flow trigger. There also remains the possibility that the slipface slope is more easily destabilised by primary flows due to the accumulation of sediment from a ‘lock up zone’ or mid slope particle settling.

More recently, the exploration of complex airflow patterns in the lee side of aeolian dunes using high resolution computational modelling has suggested a possible role for turbulent winds disturbing areas of the slipface and increasing potential to trigger grainflow. For example, secondary lee slope flow patterns generated by flow separation at the dune crest and the subsequent reattachment flow have been observed to produce complex eddies and vortices (Parsons et al., 2004a,b; Jackson et al., 2013a,b; Pelletier et al., 2015; Smith et al., 2017a,b). While the role of these complex
airflow patterns in sediment transport on the lee side of a dune is not well understood, they may have a significant localised effect on surface shear stress, resulting in sediment redistribution (e.g. Wiggs, 2001; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005). Pelletier et al. (2015) demonstrated that the angle of initial yield can decrease with increasing wind velocities, leading to grainflows at lower critical angles than otherwise possible and another study noted that oblique incident airflow can result in deflected lee-flow, which promotes lateral transport of sediment on a slipface (Walker, 1999). Research is ongoing in the investigation on how lee slope airflow patterns potentially affect surface shear stress and sediment transport and may be useful in distinguishing various grainflow formation mechanisms.

2.1.3 Grainflow Magnitude

Grainflow magnitude is under debate in the aeolian community. There is a dearth of information related to grainflow surface area as well as flow thickness. Previous studies have discounted a connection between sediment flux (wind velocity) and grainflow magnitude where only a relationship between grainflow frequency and sediment flux was observed (McDonald and Anderson, 1995; Cupp et al., 2005; Breton et al., 2008; Sutton, 2012; Sutton et al., 2013a,b; Pelletier et al., 2015). In contrast, Nield et al. (2017) argued that there was a correlation between grainflow frequency as well as magnitude with greater wind velocity where weaker winds produced smaller grainflows near the dune brink and stronger winds triggered avalanches further downslope resulting in more sediment being mobilised upslope. Additional field observations are
needed to resolve the inconsistency of the relationship between wind velocity and grainflow magnitude and frequency.

Related to the topic of grainflow magnitude and the formation mechanism of large grainflows is the hypothesis that grainflow thickness directly correlates with dune height. This relationship has been used to estimate paleo dune heights from aeolianite deposits (e.g. Kocurek and Dott, 1981; Sweet et al., 1988; Kocurek, 1991) but it has not been extensively tested with modern day field observations of grainflow thicknesses involving a variety of dune heights and morphologies. Field observations have been made of thick, large areal extent grainflows (e.g. McDonald and Anderson, 1995; Nickling et al., 2002; Breton et al., 2008) but what triggers these flows and an exact definition of what qualifies as ‘large’ has not yet been determined.

There is a possibility that the formation of large (or thicker) grainflows is not entirely controlled by dune height and may be influenced from environmental conditions or involve an alternative formative mechanism (e.g. McDonald and Anderson, 1995). For example, the expansion of sediment suspension and saltation trajectories on the slipface during high velocity winds was observed to transform the localised bulge of sediment near the dune brink into a large wedge of sediment, and accumulate more sediment mid slope resulting in much larger grainflows on dunes (e.g. Nickling et al., 2002; Cupp et al., 2005; Nield et al., 2017). It has also been suggested that larger grainflows on dunes may increase in thickness and areal extent if sediment is entrained from the disruption of unstable grains deposited in the ‘lock up zone’ mid slope (e.g. McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and
Anderson, 1996; Nickling et al., 2002). Both examples of high-magnitude grainflows occur on large dunes but the specific relationship between height and flow thickness has not been constrained.

2.1.4 Grainflow Classification

Descriptions of variations in grainflow planform morphology, are extremely scarce in the literature, however, they may be the key to consolidating knowledge of grainflow dynamics across a wide range of aeolian settings. With the growing literature and interest by researchers in slipface processes, there is now a need to provide a structure to support discrete observations of grainflows between different aeolian environments. Grainflows likely operate on a dynamic continuum, meaning that similar formation mechanisms and morphologies exist over a wide range of aeolian environments. Differing grainflow morphologies and magnitudes may indicate failure mechanisms due to the influence of the local wind regime, turbulent wind patterns on the lee slope, grain characteristics, or other environmental factors such as presence of salts or liquid/frozen water. Therefore, a classification of grainflow types based on surface area and planform shape is useful for comparative studies across a range of aeolian environments.

The classification for grainflows introduced in this paper aims to quantify their morphometric characteristics. It builds upon previous work but is based on new observations of formation patterns and morphology. It is not intended to be exhaustive
and is flexible to future expansion with the potential for additional grainflow morphologies from different wind regimes and climatic environments.

This study constrains grainflow thickness using sub-millimetre resolution 3D laser scans along with simultaneous video documentation. This allows better estimates of the volume of redistributed sediment for each grainflow morphology. In addition, there is a need to undertake further work to distinguish the controls on the specific styles of flows so that classification can be usefully linked to controlling parameters from environmental factors such as climate and wind regime to more detailed secondary airflow patterns as well as influences from physical grain characteristics, and dune morphology. Further work in these areas would benefit the interpretation of aeolian deposits (e.g. McKee et al., 1971; McKee and Bigarella, 1972; Morris et al., 1972; Bigarella, 1975; Hunter, 1977; Borowka, 1979; Fryberger and Schenk, 1981; Sweet and Kocurek, 1990; Bourke, 2005; Anderson and Walker, 2006) and further elucidate paleoenvironments of aeolianites (e.g. Kocurek and Dott, 1981; Sweet et al., 1988; Kocurek, 1991; Eastwood et al., 2012).

2.2. Data and Analysis Techniques

2.2.1 Field Location and Sediment Characteristics

The study site is in the central region of the Maspalomas dune field, which has a total area of about 4 km² and is situated on the southern end of Gran Canaria island, Spain (Hernandez et al., 2017). All observations collected took place ca. 500 meters inland from the ocean at 27° 44’ 41.2” N 15° 34’ 23.8” W on a large transverse dune. The dune field is comprised of several large transverse dunes, decreasing in size and
transitioning to a mixture of small transverse and barchanoid dune shapes to the east. This dune field was chosen because of the arid climate, where the annual precipitation is <100 mm yr\(^{-1}\) (Marzol, 1987), resulting in sparse vegetation, and regular aeolian activity, thus making it a suitable field site for dune morphodynamic studies. Observations were collected on 8 December 2014, during the winter season when the eastern and northeastern winds are the strongest and have the most influence on dune migration (Hernandez et al., 2002; Jackson et al., 2013\(_b\); Hernandez et al., 2014; Smith et al., 2017\(_b\)).

Meteorological data was retrieved from a weather station located approximately 2.5 km southwest of the study site (27° 44' 09.0'' N 15° 35' 45.2'' W). Between 10:04 am and 12:50 pm (Western European Time Zone) on 8 December 2014, during the time of field observation, the Maspalomas weather station recorded an average temperature of 21°C, humidity levels around 52%, and wind from ~55° (northeast) with an average wind velocity at 1 m height of 9.51 m s\(^{-1}\) (±0.09 m s\(^{-1}\)) and a maximum gust speed of 23.14 m s\(^{-1}\).

Sediments in the Maspalomas dune field are composed of a mixture of calcium carbonate/biogenic marine materials (Alcantara-Carrio, 1998; Hernandez et al., 2002) and phonolitic rocks weathered from the island volcanic deposits (Martinez, 1986) with an average grain size of 220 μm (Alacantara-Carrio, 1998). Although a compositional analysis was not conducted on the sediment at the study site, components of both carbonate/biogenic marine materials and volcanic deposits were recognised in the sediment samples. The darker, volcanically-derived sediments were easily distinguished
from the carbonate marine materials due to aeolian sorting effects, where the volcanic sediments concentrated on ripples and were frequently observed coalescing along the edges of an active grainflow. Six sediment samples were collected at the study site, including the surface of the lower stoss slope, mid stoss, crest, mid lee, lower lee slope, and interdune and measured by laser diffraction. An average grain size of 244 µm was measured for the entire sand dune (excluding the interdune) and is consistent with the grain size analysis reported by Alacantara-Carrio (1998).

Larger grains were present on the stoss slope, with a 50th percentile of 304 µm on the lower stoss slope and 218 µm mid stoss. The range of grain sizes for the lower and mid stoss slope was between 86 - 756 µm and 76 – 516 µm, respectively. The 50th percentile for grains collected from the dune crest was 254 µm with a range of 98 - 586 µm. The 50th percentiles for the mid lee slope and lower lee slope were 214 and 229 µm, respectively and had identical grain size ranges between 76 - 516 µm. Lastly, the 50th percentile for interdune sediment was 194 µm, ranging between 14 – 516 µm grain sizes. These grain sizes do not include any salt component because the laser diffraction measurements were conducted in water, thereby dissolving any salt component. Water and salt weight percentages of each sediment sample were calculated by weighing samples before and after overnight drying took place in an oven and prior to laser diffraction measurements. These percentages were calculated to investigate any potential influences of moisture on grainflow formation.

Particle-size distribution was investigated prior to laser diffraction measurements to identify a potential salt component in the sediment samples.
splitting was conducted followed by standard sieve analysis using a series of nested sieves with quarter phi set. Salt was easily identified in all the sediment samples after sieving took place because salt entirely comprised grain sizes less than 100 µm. The weight percentages for salt presented here are likely an underestimate depending on how much salt was dislodged from sand grains during the sieving process. There was no detectable amount of moisture in the sediments collected on the dune but there was a small amount of salt, ranging from 0.7% weight near the crest to 3.4% weight near the base of the slipface. The interdune sediment sample contained about 2.6% water weight with 16.2% weight salt. Knowledge of water and salt components in the sediment may be useful for future studies conducting similar grainflow observations under differing environmental conditions and a better understanding of the relationship between moisture and grainflow styles may be formulated.

2.2.2 Slipface Observations

Data collection included a series of ground-based laser scans, video recordings, and images taken on a portion of a slipface of a large, transverse dune (Fig. 1; located at 27° 44’ 41.2”N, 15° 34’ 23.8”W). Twenty five consecutive laser scans of the slipface began at 10:00 am and continued until 12:50 pm using a FARO Focus 3D X 330 terrestrial laser scanner with a laser beam wavelength of 1550 nm. Simultaneous video recording occurred between 9:55 and 11:20 am. Observations were collected during this time of day when winds were the strongest and the most consistent and had no periods of calm
or inactivity in sediment transport.

The FARO Focus 3D X 330 is designed to capture fast and accurate measurements of complex objects or buildings, making it ideal for recording detailed measurements of grainflows in the field. The scanner is calibrated yearly to guarantee accuracy and precision, minimizing data error from the electronic, distance, intensity, temperature and angular sensors and inclinometer. Faro Focus 3D X 330 has a scan range distance between 0.6 mm to 330 m with a ranging error of ±2 mm at 10 m and a ranging noise error at this distance of 0.3 mm with 90% reflectance and 0.4 mm with 10% reflectance. These error and noise estimates increase at greater distances. The measurements collected in this study were about 1.5 m from the lee slope, well within

Figure 1. Maspalomas dune field, Gran Canaria, Spain study site location (located at 27° 44’ 41.2’’N, 15° 34’ 23.8’’W). Displayed here are satellite images of Gran Canaria island (upper left), where the white box represents the extent of the dune field magnified in the middle image. The red dot represents the location of the study site within the dune field and is magnified in the upper right hand box where the black circle shows the location of the slipface for this study. Green lines indicate dune crests and orange outlines indicate interdune areas. White arrow represents wind direction on the day of observation.
the 10 m distance for the above mentioned error estimates, and were collected at full resolution (0.61mm m⁻¹, or about 160,000 points/degree), producing a high-density point cloud totalling approximately 28.6 million data points.

The study site dune had a height of approximately 9.62 m and a lee slope of 31.04°, as measured by the ground-based, high-resolution laser scanner. A 5-meter span of the slipface, directly in front of the TLS is where the highest resolution observations were recorded is referred to here as the ‘main slipface’ (Fig. 2). The main slipface was

![Diagram of grainflow volume calculation](image)

**Figure 6.** Calculation of the volume of a grainflow using a wedge to approximate the flow morphology, where \( b \) is the thickness of the grainflow at the base of the flow, \( h \) is the height of the grainflow normal to the substrate, \( a \) is the width of the grainflow at the base of the flow, and \( c \) is the width of the grainflow near the initiation point. Length (\( L \)) of the grainflow is used to calculate the height of the grainflow using the sine of the angle of repose (32.15°) of the dune slipface. Thickness of the sediment at the base of the grainflow is doubled and then the entire volume of the wedge is halved to reflect the half of the wedge representing the grainflow situated on the slipface.
perpendicularly intersected by a larger dune form (Fig. 1), resulting in a smaller portion of the slipface that was exposed. This exposed portion had a slipface height of 2.2 m and a slope of 32.15°. Laser scan data were primarily used to quantify change on the slipface slope and observations were set to record a 180° view approximately 1.5 m from the base to the slipface, thereby capturing the entire 2.2 m-high main slipface section as well as portions of the larger 9.62 m-high slipface. Three target boards were placed around the study site and RTK GPS points were taken of each target location to allow for accurate spatial comparisons between each laser scan. Laser scans were taken at eight-minute intervals from 10am to 12pm at full resolution. Between 12pm and 1pm the scan frequency was increased to four-minute intervals, whilst retaining the resolution. Video footage and images of the lee slopes were taken concurrently with the laser scans between 9:55 am – 10:21 am, 10:40 am – 11 am, and 11:14 am – 11:20 am using an iPad with 1080p HD video recording at 30 frames per second and 8-megapixel photos.

Post-processing of the laser scans involved filtering the data using FARO SCENE software. The filters applied to each individual scan included a dark scan points filter, a distance filter, and a stray filter. Each of these filters minimized noise and eliminated erroneous data points that can be common in laser scan data. The dark scan points filter is defined by a reflectance threshold where dark points (having weak signals and low accuracy) below the defined threshold value are removed. The distance filter can be specified for any distance and points greater than that distance are deleted. This filter was useful for minimizing noise from particles, such as airborne sediment. Lastly, the stray filter removed edge effects and other outliers from the dataset.
2.2.3 *Grainflow Morphologies and Volume Estimates*

Four types of grainflows were identified in this study. They were classified using their surface area of grainflow and planform shape. All calculations of area and volume estimates were conducted using ground-based laser scan data registered with RTK GPS points. Volume estimates were determined using the polygonal area of redistributed sediment on the slipface in ArcMap and measurements of grainflow thicknesses were collected using SCENE software.

Despite having high resolution scans of grainflows, deriving volume estimates of sediment from some individual flows proved difficult and unreliable primarily due to the amount of noise from airborne sediment and secondarily to the highly dynamic nature of the slipface. Noise from airborne sediment increased upslope near the brink, complicating the delineation of surface points and laser points bouncing off the sediment cloud. Removing the sediment cloud left behind small ‘shadow zones’ on the upper slopes of the slipface, where the laser could not penetrate to the surface. These occluded survey locations precluded an accurate area measurement of grainflow areas using software techniques but their extent was otherwise easily discerned by an observer.

In cases where noise from airborne sediment was more subdued, another difficulty arose due to the time lapse between scans. Ideally, a volume estimate of redistributed sediment from a single grainflow could be derived if a previous scan recorded an undisturbed slipface surface prior to a grainflow event. However, it was
rare that each grainflow that was scanned had a previous scan of the same area
undisturbed prior to the flow. Smaller grainflows occurred every 30 seconds across the
entire slipface and larger grainflows occurred every two to three minutes. Laser scans in
this study recorded a 180° view every four to eight minutes making it difficult to capture
the ideal conditions for a reliable volume estimate of each individual grainflow.

Therefore, a modified formula of a wedge was used to approximate the shape of
the grainflows and estimate the volume of sediment displaced for each grainflow. A
wedge is used to approximate the thickening of grainflows downslope from their
initiation point and is represented by the following formula:

\[ V = \frac{1}{2} \left( \frac{bh}{6(2a + c)} \right) \]

Where \( b \) is twice the thickness of the grainflow at the base of the grainflow, \( h \) is the
height of the grainflow normal to the dune substrate, \( a \) is the width of the base of the
grainflow, and \( c \) is the width of the grainflow near the initiation point (Fig. 2). Height is
calculated by taking the sine of slipface slope angle (32.12°), multiplied by the length of
the grainflow on the slipface surface. The volume of the wedge is halved to approximate
a single side of the wedge, representing the grainflow level with the slipface surface. For
each grainflow, flow thicknesses were measured in three locations along the edge of the
flow, including immediately below the initiation point, midway down the flow, and the
base (source sink) of the grainflow (Table 1) to ensure that there was a gradual
thickening of sediment as assumed by the wedge formula. These measurements do not
account for any potential concavity of the underside of the grainflow and only include
areas of redistributed sediment, excluding other features
Table 1. Grainflow measurements including the initiation point, dimensions of the flows, and estimates of grainflow area and volume of redistributed sediment for each morphology. Measurements are given in centimetre units. Morphologies marked with and asterisk (*) indicate grainflows that occurred on the main slipface shown in Figures 3, 4, and 5. Some initiation point measurements for hourglass grainflows could not be measured due to noise from airborne sediment or inadequate video coverage.

<table>
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<th>Initiation Point Grainflow Thickness</th>
<th>Midpoint Grainflow Thickness</th>
<th>Base Grainflow Thickness</th>
<th>Grainflow Length</th>
<th>Initiation Point Grainflow Width</th>
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associated with the flow such as alcoves and incised ‘channels’ upslope of the grainflow deposit.

An attempt was made to test the accuracy of the wedge formula by restoring a small portion of the slipface with a recent grainflow to pre-grainflow conditions from a single laser scan. The grainflow selected from the scan data (#15, Table 1) had lower amounts of noise to reduce error in volume calculation. To restore the slipface, the data points containing the grainflow were removed, leaving the surrounding, undisturbed slipface on either side of the flow. The remaining data points were used to interpolate the surface prior to the flow event. Volume was then calculated by subtracting the interpolated slipface surface from the surface with the grainflow.

The calculated volume using an interpolated surface of grainflow #15 was approximately 4,348 cm$^3$, where the wedge method estimated a volume of 5,398 cm$^3$ (Table 1). It is likely that the volume estimates using an interpolated surface are underestimates, especially higher upslope where the grainflow cut into the slipface below the alcove. Any redistributed sediment deposited below the interpolated surface was calculated as negative volume. The volume calculations using the wedge formula include all redistributed sediment from a grainflow, including sediment deposited where the grainflow cut into the slope. Considering the uncertainty introduced in restoring the slipface via interpolation and how redistributed sediment volume was calculated, these two estimates appear to agree well.

Locations of grainflow initiation were primarily isolated through GPS-registered laser scans. In cases where high levels of noise were present, the grainflow initiation
point was approximated using still frame images from video recordings using the GPS-registered target boards to constrain location (Table 1). Airborne sediment ejected from the dune brink introduced significant amounts of noise at the top of the slipface in the laser scans and entirely obscured approximately 10-20 cm of the lee slope just below the brink. Therefore, grainflows that initiated near the brink were measured in ArcMap using images captured from video. A few grainflows reported in Table 1 do not include an initiation point because the laser scan captured the grainflow after the alcove had already formed, making it difficult to estimate the exact initiation point, and there was no concurrent video record to indicate the exact location of initiation.

Lastly, overall horizontal slipface advancement was approximated using two laser scans 92 minutes apart. The horizontal change (slipface advancement) was determined by taking the difference of the two laser scans in ArcMap GIS, imported with 1 cm gridding. This provided a visual representation and quantified slipface advancement during observation.

2.3 Results

2.3.1 Grainflow Morphology

Grainflows displayed a variety of morphologies during observation in the Maspalomas dune field (Fig. 3, 4, and 5). Previous grainflow classifications have broadly separated ‘primary’ and ‘secondary’ flows (Breton et al., 2008). The distinction focused on potential triggers of grainflow activity but did not distinguish between differences in morphology and respective sediment loads. Initiation of primary flows is attributed to
the accumulation and destabilization of a sediment bulge centimetres below the dune brink on the slipface. Secondary flows are generally smaller and thought

Figure 3. Example of an ‘hourglass’ grainflow in the Maspalomas dune field in Gran Canaria, Spain. ‘Hourglass’ flows initiate tens of centimetres from the dune crest (left), eventually developing an alcove with a broadened sediment fan below (right). Time progression between the left and right images is approximately 13 seconds. The checkered A4 paper (21 x 29.7 cm) on target board at the crest of the dune was used for GPS registration and can be used for background scale of the slipface. A foreground scale is provided in the lower right-hand corner. Slipface height is approximately 2.2 meters.

Figure 4. An example of a ‘slab’ flow in the Maspalomas dune field, Gran Canaria, Spain. These flows begin with the appearance of horizontal tensile cracks in close proximity and parallel to the dune brink (emphasized by arrows on the left). Sediment is mobilized shortly after tensile cracks appear (right). Time progression between the left and right images is approximately 5 seconds. The checkered A4 paper (21 x 29.7 cm) on target board at the crest of the dune was used for GPS registration and can be used for background scale of the slipface. A foreground scale is provided in the lower right-hand corner. Slipface height is approximately 2.2 meters.
to be initiated in response to disturbances from primary flow activity.

The basic distinction between ‘primary’ and ‘secondary’ flows (Breton et al., 2008) is retained in this paper but is extended by identifying subsets of flow features with morphological descriptions and quantifying sediment redistribution volumes for each. New terminology (‘hourglass’, ‘slab’ ‘lobe’ and ‘funnel’ flows) is introduced to further distinguish different flow types based on morphology. A total of 71 grainflow events were captured during laser scanning and approximately 30 of these were also recorded on video. For each grainflow type, the location of flow initiation, areal extent, grainflow thickness, and volume estimates of redistributed sediment are quantified and discussed.
2.3.1.1 *Hourglass Grainflows.*

Sediment flows observed in wind tunnel experiments and field observations display a localised over-steepening of the slipface from the formation of a sediment ‘bulge’ a short distance from the dune brink due to an accumulation of sediment by grainfall, saltation, and reptation (e.g. Bagnold, 1941; Allen, 1968; Allen, 1970; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1995; Nickling et al., 2002; Cupp et al., 2005; Sutton, 2012; Sutton et al., 2013a,b). The subsequent initiation of the grainflow results in the formation of an alcove via scarp recession just below the crest that spreads upward and expands laterally (Lindsay, 1973; Hunter, 1977; Sutton, 2012; Sutton et al., 2013b). The alcove grows as sediment flows downslope, and forms a bottleneck at the point of steepest gradient on the slipface (Anderson, 1988) then the sediment accumulates as a fan at the base of the lee slope. In this study, these types of previously observed sediment flows are referred to as ‘hourglass’ grainflows based on their morphology (Fig. 3 and 6). They are considered a type of primary grainflow as they are a direct response to localised slope steepening, independent of other grainflow activity.

The ‘hourglass’ morphology occurred frequently at the Maspalomas study site and tended to move moderate amounts of sediment, relative to ‘lobes’, ‘funnels’, and ‘slab’ grainflows. The 28 ‘hourglass’ flows recorded affected areas between 4,352 and 23,624 cm² on the slipface, averaging 10,979 cm² (Table 1). The point of failure of the grainflow ranged between 27 and 36 cm downslope from the brink, consistent with previous studies (e.g. Anderson, 1988; Nickling et al., 2002; Breton et al., 2008).
Figure 6. Simplified illustrations of grainflow morphologies identified in this study, including (A) ‘hourglass’ flows with alcove, (B) ‘funnels’ and ‘lobes’ and (C) ‘slab’ flow. ‘Lobe’ and ‘funnel’ morphologies in panel (B) are differentiated using ‘L’ and ‘F’ labels, respectively. No scale has been provided because these grainflow morphologies may have the potential to be spatially larger or smaller depending on the scale of the dune form and environment.
Grainflow thicknesses ranged from ca. 0.1 to 8 cm with an average thickness of 1.43 cm. The average estimated volume of redistributed sediment from these ‘hourglass’ flows per flow event was approximately 22,494 cm$^3$, ranging between 582 cm$^3$ (a grainflow in progress) to 85,891 cm$^3$.

2.3.1.2 Slab Grainflows.

Larger grainflows have been mentioned in previous work as ‘large area extent’ grainflows (e.g. McDonald and Anderson, 1995; Nickling et al., 2002; Breton et al., 2008) but these grainflows have not been rigorously studied. In the absence of a clear description of trigger mechanisms or spatial or temporal quantifiers (e.g. estimates of area dimensions, formation frequency, flow duration), ‘slab’ flows might be one of these ‘large areal extent’ flows or a new type of large primary grainflow. In this study, ‘slab’ flows, affected large areas of the slipface, ranging from 210,779 to 685,563 cm$^2$, and each mobilised a large volume of sediment that successfully reached the base of the slipface in one episode. The initiation point of these grainflows was first visible in the form of uneven horizontal tensional cracks appearing at variable distances parallel to the brink (Fig. 4 and 6). The tensional cracks commonly appeared within 2 to 12 cm of the brink, with an average initiation location of about 5.83 cm from the brink. ‘Slab’ flows were relatively rare compared to the other grainflows with only 7 events captured during observation, most of which occurred on the longer slipface slopes of the dune (Table 1). Grainflow thicknesses increased downslope and ranged from 0.07 to 5.52 cm with an average thickness of 1.04 cm. The volume of sediment moved by these
grainflows per flow event was estimated to range between 103,724 and 559,334 cm$^3$ with an average volume of 182,111 cm$^3$.

2.3.1.3 Lobe and Funnel Grainflows.

Secondary grainflows are significantly smaller than primary flows and have been observed to occur shortly after larger grainflow events (Breton et al., 2008). Smaller grainflows were also observed to form seconds before large grainflow events during the Maspalomas observations and were often obscured by the overriding primary grainflow. The smaller Maspalomas grainflows initiated in localised areas of slope destabilization, specifically where alcove walls failed or in areas where previous grainflows “locked up” mid-slope (McDonald and Anderson, 1995). Two types of distinct secondary grainflows were observed (Fig. 5 and 6), referred to here as ‘lobes’ and ‘funnels’. Nearly all observed ‘lobe’ and ‘funnel’ grainflows formed in the mid-slope region of the slipface. The ‘lobe’ and ‘funnel’ grainflows that occurred higher upslope, near the brink, were frequently triggered by the failure of an alcove wall from an ‘hourglass’ grainflow. ‘Lobes’ and ‘funnels’ typically formed independently of each other but in some cases, there were clusters of activity where two or more flows initiated at the same time or seconds apart from each other at various locations of the slipface. In other cases, a single ‘lobe’ or ‘funnel’ flow formed without any further activity.

‘Lobes’ were typically thin, broad, flattened features that rarely transported sediment to the base of the slipface. A total of 25 ‘lobe’ morphologies were identified in the laser scan data (Table 1). Grainflow thicknesses of ‘lobes’ averaged about 0.77 cm
and thinned upslope to the point of initiation and sometimes thinned downslope as well. These flows moved small amounts of sediment, averaging about 1944 cm$^3$ per flow event and ranging between approximately 124 cm$^3$ to 5,091 cm$^3$.

‘Funnel’ grainflow morphologies distinctly manifested as long, linear features that transported small amounts of sediment downslope through a shallow, narrow trough (Fig. 5 and 6). In contrast to ‘lobes’, ‘funnels’ often successfully delivered sediment directly to the base of the slipface where it accumulated in a small depositional fan. These grainflows were quickly infilled, making it difficult to measure and identify them in the laser scan data and therefore only 9 ‘funnel’ morphologies were identified in the laser scans with confidence (Table 1). From the few measurements collected, ‘funnel’ flow troughs averaged 1.89 cm in depth, and had widths ranging from about 2 cm to 5 cm. The average sediment thickness, deposited at the base of the slipface from ‘funnel’ flows, was measured to be approximately 1.19 cm and tapered in thickness upslope. The estimated volume of sediment transported downslope by ‘funnel’ flows averaged about 1,312 cm$^3$ with a range of about 60 cm$^3$ to 6,386 cm$^3$.

2.3.2 Frequency and Magnitude

In addition to measurements from laser scans, video coverage of the main slipface (the 2.2 m-high exposed slipface portion of the larger 9.62 m dune; Fig. 1 and Fig. 2) between 10 and 11 am provided the means to investigate frequency of grainflow occurrence. This was used to compare to the results of Breton et al. (2008).
Table 2 lists the frequency of grainflows along with the grainflow morphology corresponding to grainflows listed in Table 1. Breton et al. (2008) reported 21 grainflows over 1 hour of observation along a 14-meter stretch of slipface of a 5-m high linear dune with wind speeds between 7.38 and 7.49 m/s at a height of 0.5 m.

Table 2. Duration of grainflows observed on the main slipface shown in Figures 3, 4, and 5 with video coverage and scan data. Grainflow failure numbers correlate with the failure numbers shown in Table 1. Grainflows 1 and 4 of the main slipface were only partially recorded and have not been included in this table. The start time for grainflow 6 is uncertain because video recording began at 9:55:38 AM, seconds after its formation. Grainflows 6, 8, and 9 are from a separate video recording and do not have a time continuum with the remaining grainflows in this table which were all recorded in the same video.

<table>
<thead>
<tr>
<th>Failure Number</th>
<th>Morphology</th>
<th>Start Time (h:min:s)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Hourglass</td>
<td>~9:55:38</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Hourglass</td>
<td>10:15:06</td>
<td>27</td>
</tr>
<tr>
<td>9</td>
<td>Hourglass</td>
<td>10:15:06</td>
<td>26</td>
</tr>
<tr>
<td>41</td>
<td>Lobe</td>
<td>10:41:07</td>
<td>19</td>
</tr>
<tr>
<td>30</td>
<td>Funnel</td>
<td>10:41:08</td>
<td>15</td>
</tr>
<tr>
<td>42</td>
<td>Lobe</td>
<td>10:42:36</td>
<td>28</td>
</tr>
<tr>
<td>44</td>
<td>Lobe</td>
<td>10:42:23</td>
<td>3</td>
</tr>
<tr>
<td>35</td>
<td>Funnel</td>
<td>10:42:25</td>
<td>27</td>
</tr>
<tr>
<td>36</td>
<td>Funnel</td>
<td>10:42:30</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>Hourglass</td>
<td>10:43:08</td>
<td>28</td>
</tr>
<tr>
<td>45</td>
<td>Lobe</td>
<td>10:43:21</td>
<td>15</td>
</tr>
<tr>
<td>52</td>
<td>Lobe</td>
<td>10:43:28</td>
<td>23</td>
</tr>
<tr>
<td>53</td>
<td>Lobe</td>
<td>10:43:37</td>
<td>8</td>
</tr>
<tr>
<td>19</td>
<td>Hourglass</td>
<td>10:48:15</td>
<td>19</td>
</tr>
<tr>
<td>54</td>
<td>Lobe</td>
<td>10:52:19</td>
<td>15</td>
</tr>
<tr>
<td>22</td>
<td>Hourglass</td>
<td>10:55:18</td>
<td>20</td>
</tr>
<tr>
<td>58</td>
<td>Lobe</td>
<td>10:55:18</td>
<td>26</td>
</tr>
<tr>
<td>60</td>
<td>Lobe</td>
<td>10:55:19</td>
<td>4</td>
</tr>
<tr>
<td>70</td>
<td>Slab</td>
<td>10:55:39</td>
<td>15</td>
</tr>
<tr>
<td>26</td>
<td>Hourglass</td>
<td>10:55:37</td>
<td>44</td>
</tr>
</tbody>
</table>
The grainflows had an average area of 32,800 cm$^2$ and occurred in ‘temporal clusters’ with an average reoccurrence of 2.7 minutes.

The main slipface of the Maspalomas study site exhibited similar clusters of activity separated by brief periods of inactivity which was accentuated directly after large grainflows occurred (Table 2). The Maspalomas grainflow activity differs slightly from Breton et al. (2008) in terms of the time in between flows, duration of grainflow activity, and area estimates (Table 1 and 2). Maspalomas grainflows occurred more frequently (on average every minute) over a smaller area of slipface. The grainflows were also of shorter duration, averaging about 20 seconds. Including all grainflows from Table 1, the spatial area was generally smaller. ‘Hourglass’ grainflows averaged 11,000 cm$^2$, and ‘funnels’ and ‘lobes’ averaged between 200 and 2,900 cm$^2$, respectively. ‘Slab’ flows (averaging 425,000 cm$^2$) were the outlier regarding surface area measurements, far exceeding any grainflow reported in Breton et al. (2008).

2.3.3 Slipface Advancement

For the calculation of slipface advancement, laser scan data were restricted to a smaller portion of the slipface, overlapping with the main slipface, to investigate the relationship between grainflow activity and slipface advancement. Based on laser scan measurements and video recordings, within 92 minutes of observation, approximately 277,832 cm$^3$ of sediment was redistributed by 22 different grainflows on the main slipface (Table 1), equivalent to nearly half a metric ton of sediment. ‘Hourglass’ flows were responsible for redistributing about 51.6% of that sediment. The single recorded
‘slab’ flow for this portion of the slipface moved approximately 103,724 cm³ of the sediment, (about 43% of the total). Secondary flows redistributed minor amounts of sediment comprising the remaining 5.4% of the volume total.
Figure 7 is a difference map of the two laser scans illustrating slipface advancement within the 90-minute observation for an 8-meter span of the slipface, overlapping with Figures 2, 3, 4, and 5. The difference map shows some portions of the slipface advanced about 17 cm within this time. Using ArcMap and restricting the slipface area to a span of 5 meters to correlate with the area of the main slipface, the volume difference between these scans was also calculated and resulted in a total of about 1,185,000 cm$^3$ of sediment.

2.4 Discussion

2.4.1 Grainflow Formation

The in situ field observations and high resolution-measurements reported here provide new insights into morphodynamics of different grainflows and enable genetic insights into various grainflow forms. ‘Hourglass’ morphologies are the best documented while smaller ‘lobe’ and ‘funnel’ morphologies are poorly known. The formational cause of particular grainflow morphologies and the genetic relationships between various flow types are unknown. A few alternative formation mechanisms have been proposed to explain the occurrence of spatially-small and large flows that do not result in an hourglass morphology. The various grainflow types are discussed below.

2.4.1.1 Hourglass Flows

The most widely discussed grainflow phenomenon involves the formation and failure of a bulge or larger wedge of sediment tens of centimetres downslope from the
dune brink due to the accumulation of saltating sediment and rainfall. While the laser scan data in this study were not capable of observing the presence or growth of a sediment bulge/wedge due to noise near the dune brink, the location of failure downslope from the brink in relation to this pattern of sediment accumulation is consistent with previous studies (e.g. Allen, 1968; Allen, 1970; Borowka, 1979; Hunter, 1985; Anderson, 1988; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005; Kok et al., 2012; Sutton et al., 2013a,b).

Failures associated with the accumulation of a sediment bulge or wedge consistently correlated with the subsequent formation of an ‘hourglass’ grainflow as observed in previous field studies and wind tunnel experiments (e.g. Allen, 1968; Allen, 1970; Hunter, 1977; Borowka 1979; Fryberger and Schenk, 1981; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1992; McDonald and Anderson, 1995; Tischer et al., 2001; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005; Dasgupta and Manna, 2011; Kok et al., 2012; Sutton, 2012; Sutton et al., 2013a,b; Nield et al., 2017). The difference between small and large ‘hourglass’ flows may relate to wind velocity. Stronger winds increase the saltation trajectory of grains transported over the dune brink, resulting in the formation and subsequent failure of a large sediment wedge as opposed to a small bulge (Nickling et al., 2002; Cupp et al., 2005).

2.4.1.2 Funnel and Lobe Flows

Factors invoked to explain other grainflow morphodynamics include disturbance from large grainflows, mid slope accumulation of sediment, and lee side airflow
patterns. The formation of ‘funnel’ and ‘lobe’ flows may be influenced by one or more of these factors. Breton et al. (2008) observed that smaller ‘secondary’ flows formed as a direct response to disturbance from larger ‘primary’ flows, and they occurred soon after the formation of the ‘primary’ flow. Some of the ‘lobe’ flows in this study also occurred as a direct result of disturbance from larger flows. Typically, the collapse of an alcove wall from an ‘hourglass’ flow produced a smaller ‘lobe’ flow. In a few instances, the tongue of the ‘hourglass’ flow disturbed nearby sediment as it moved downslope, triggering simultaneous smaller ‘lobe’ flows. None of the ‘funnel’ flows were associated with ‘hourglass’ flows but they often occurred with ‘lobes’ on the mid to lower lee slope preceding a larger flow. The occurrence of smaller flows prior to and independent of larger flows differs from the observations of Breton et al. (2008) and requires a different trigger mechanism.

The accumulation of sediment mid slope due to a ‘lock up zone’ (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996) or the increase of aeolian transport during stronger winds (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996; Nickling et al., 2002; Nield et al., 2017) are both potentially valid alternative formation mechanisms of ‘lobe’ and ‘funnel’ flows that form independent of ‘hourglass’ flows. It is possible that sediment from previous grainflows that did not reach the base of the slipface accumulated mid slope in this ‘lock up region’, facilitating the buildup and destabilization of sediment. In addition, observations took place during strong wind
conditions (9.5 m s⁻¹) which likely increased the downslope distance of where sediment settled, augmenting the accumulation of sediment in this mid slope region.

Secondary lee slope air flow patterns generated by flow separation at the dune crest and subsequent reattachment flow generate complex eddies and vortices which affect surface shear stress and sediment redistribution (Wiggs, 2001; Walker and Nickling, 2002; Parsons et al., 2004a,b; Cupp et al 2005; Jackson et al., 2013a,b; Pelletier et al., 2015; Smith et al., 2017a). As more airflow modelling is conducted, the effect of lee side airflow patterns on the initiation of ‘lobe’ and ‘funnel’ flows may become better understood and a direct link to turbulent airflow and localised slope destabilization may be discovered (e.g. Walker, 1999; Walker and Nickling, 2002). ‘Lobe’ and ‘funnel’ flows may also be sensitive to the magnitude and direction of wind, where increasingly stronger winds can decrease the angle of initial yield leading to an increase of failures (Pelletier et al., 2015), and oblique incident airflow may promote lateral redistribution of sediment on the slipface (Walker, 1999).

2.4.1.3 Slab Flows

Large flows appear to be initiated by grainfall and grain saltation, similar to ‘hourglass’ flows, however, differences in scale and morphology suggest an additional process influences the initiation of these spatially-large flows. Potential influences include moisture content (e.g. McKee et al., 1971; McKee and Bigarella, 1972; Morris et al., 1972; Bigarella, 1975), complex air flow cells on the lee side of the dune, or an alternative failure process.
The presence of moisture is an obvious explanation for the formation of ‘slab’ flows, especially for coastal dunes which may have varying degrees of internal cohesion. Heavy rainfall occurred three days before with some light rainfall the night before observations in this study. Despite the absence of detectable moisture in the sediment samples, internal layers of damp and dry sand could potentially influence the style of grainflow. Layers of relatively dry sand would provide a failure plane for large slabs of sediment such as those observed in this study. Similar cohesion is also thought to be present in polar aeolian deposits with alternate layers of snow, ice and sediment (e.g. Morris et al., 1972) but few field observations have been done in these environments and there are no known descriptions or observations of ‘slab’ flows on polar dunes.

Another explanation for the initiation of spatially-large grainflows may involve complex airflow cells which carry and deposit sediment in the lee of the dune (McDonald and Anderson, 1995; Nickling et al., 2002). It is possible that sediment transported in flow cells may provide additional sediment, thereby increasing the magnitude of grainflows (Nickling et al., 2002). Cupp et al. (2005) showed from wind tunnel experiments that sediment deposition on the lee slope involves two transport zones. In the upper part of the lee slope, fallout of saltating grains results in reptation down the slope. Below this fallout area, there is a return cell that results in very minor upslope sediment transport. It has been hypothesized that the interaction between these two transport zones may produce larger grainflows (Nickling et al., 2002; Cupp et al., 2005). However, this explanation does not match well with the morphology and the initiation location of the ‘slab’ flows observed in this study.
Lastly, Fryberger and Schenk (1981) characterised two differing mechanisms of grainflow, or failure processes, in a laboratory setting. These included scarp recession (detailing the ‘hourglass’ flow morphology) and slump degeneration. The description of the slump degeneration agrees well with the observations of ‘slab’ flows in this study. The progression of the observed slump degeneration began as a series of tensional features near the top of the artificial slipface until sediment flowed downslope forming compressional features (folds) while preserving cohesion under dry conditions (Fryberger and Schenk, 1981). The ‘slab’ flows observed in Maspalomas formed identically to this description of slump degeneration. The onset was manifest as multiple tensional cracks centimetres from the dune brink and compressional folds formed as the ‘slab’ flow began to travel downslope (Table 1 and Fig. 4). Sediment in the Maspalomas ‘slab’ flows appeared to be semi-cohesive despite the absence of detectable moisture in the sediment samples. The cause of cohesion in dry sediment was never discovered by Fryberger and Schenk (1981) but it cannot be discounted as a possible flow mechanism.

2.4.2. Sediment Redistribution

Each of the grainflow morphologies observed in Maspalomas has differing capacities of sediment transport which affects slipface advancement and dune migration. Details of these different types of grainflows will lead to a better understanding of slipface processes as well as an improved interpretation of dune stratigraphy and aeolian environment.
2.4.2.1 Grainflow Morphology and Magnitude

‘Slab’ flows displaced the greatest amount, nearly an order of magnitude greater volume than a single ‘hourglass’ flow and approximately two orders of magnitude greater than the average ‘lobe’ and ‘funnel’ flow. It therefore appears that ‘slab’ flows had the greatest influence on slipface advancement and sediment redistribution. However, ‘slab’ flows were comparatively rare and it is likely that these grainflows formed under special conditions, potentially dependent on moisture which may have added cohesion to the sediment and may not be representative of typical slipface processes.

Due to the higher frequency of occurrence during observation in Maspalomas, ‘hourglass’ flows were likely responsible for moving the most sediment downslope. The regularity and frequency in which these grainflows occurred suggest that ‘hourglass’ flows play an important role in slipface advancement. ‘Lobe’ and ‘funnel’ flows appear to play a secondary role despite sediment from these flows not reaching the base of the slipface. These grainflows commonly occurred midslope in areas on the slipface previously suggested to be ‘lock-up zones’ (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996) or zones of accumulated sediment from suspension settling (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996; Nickling et al., 2002; Nield et al., 2017). These smaller grainflows were the most frequent but were rapidly obscured by settling airborne sediment making it difficult to capture all the activity that occurred during observation. The sediment that accumulates in the mid slope from grainfall or smaller
grainflows may supply additional sediment to other grainflows, potentially creating larger magnitude flows (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996; Nickling et al., 2002), thus playing a minor role in slipface advancement.

2.4.2.2 Overall Slipface Advancement

There is a large discrepancy between the volume change of sediment on the slipface calculated from taking the difference between laser scans in ArcMap and measurements of individual grainflows alone from Table 1. Aggregated volume measurements of individual grainflows provide a total volume estimate of redistributed sediment on the main slipface of approximately 277,832 cm$^3$. In contrast, the difference of the two laser scans spanning 92 minutes indicated a total volume change of approximately 1,185,000 cm$^3$ (1.185 m$^3$) for a 5-meter span of the slipface.

This discrepancy is likely due to the fact that scans were acquired every four to eight minutes and did not capture all grainflows which typically occurred at 30 second to one minute intervals (Table 2). In addition, the discrepancy in volume estimates between individual grainflow measurements and the volume difference of laser scans may reflect how rainfall influences slipface advancement. Rainfall was responsible for triggering individual grainflows and rebuilding the slipface after an event but may have also had a significant role in slipface advancement. The precise influence that rainfall had on slipface advancement is difficult to quantify because it is a gradual process and varies depending on aeolian conditions.
2.4.2.3 Correlation of Dune Height and Flow Thickness

The thickness of individual grainflow cross-strata preserved in aeolianite deposits has been previously used as a method to estimate paleo dune height (e.g. Kocurek and Dott, 1981; Sweet et al., 1988; Kocurek, 1991). This relationship was originally suggested by Hunter (1977) and relies on the assumption that grainflow thickness is consistent on a variety of dune forms of the same height and increases in thickness with increasing dune height. While this hypothesis appears logical, there may be multiple influences not accounted for that affect the thickness of a grainflow. For example, Nield et al. (2017) observed that with increasing wind velocities, the length and thickness of grainflows also increased. Additionally, the entrainment of sediment as grainflows travel down the slipface may vary. Deposits of grainflow thickness may increase due to the addition of grains from the mid slope where sediment can become destabilised in a ‘lock up zone’ or secondary location of localised over steepening (McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996; Nickling et al., 2002; Neild et al., 2017).

The grainflows observed in Maspalomas had a variety of flow thicknesses and did not have a strong correlation with dune height (related to grainflow length; Fig. 8). The most variable grainflow thicknesses were measured from ‘hourglass’ flows, where the thicker flows possibly entrained additional sediment from the mid slope. ‘Funnel’ flows had the strongest correlation between grainflow length and thickness but also had the fewest number of observations. ‘Lobe’ flow thickness had a very weak correlation to
grainflow length but both the ‘funnel’ and ‘lobe’ flows generally did not extend the entire length of the slipface and would be a poor indicator of potential dune height. ‘Slab’ flows had the most consistent base thickness, ranging between 1 - 2 cm with one outlier of 5.5 cm thickness (Fig. 8). These flows were relatively thin compared to other grainflow morphologies but may also be affected by entrainment of additional sediment. Until more observations and measurements are collected, it is unclear how reliable grainflow thickness is as a link to dune height and should be treated with caution when interpreting paleo environments. 

Figure 8. Relationship between grainflow thickness and grainflow length. The data points of length and thickness correlate to the grainflow length and base grainflow thickness from Table 1. Similar relationships were present when plotting grainflow thicknesses from the upper and mid slope. ‘Hourglass’ grainflows (blue dots) have highly variable grainflow thicknesses where thicknesses greater than 4 cm are less common and do not correlate with grainflow length. ‘Funnel’ (red triangles) and ‘lobe’ (green diamonds) sediment flows have less variability in grainflow thickness where most thicknesses are less than 2 cm. There exists a very weak correlation with grainflow length and thickness for both types of flow but is stronger for ‘funnel’ flows. ‘Slab’ flows (orange squares) are generally thin compared to ‘hourglass’, ‘funnel’ and ‘lobe’ flows and do not have an apparent relationship with grainflow length.
2.4.3 Comparison of Grainflow Behaviour with Previous Studies

Grainflows observed in Maspalomas and those reported by Breton et al. (2008) differ slightly in behaviour but are consistent when physical differences in dune morphologies and wind regime are considered. The linear dune observed by Breton et al. (2008) was 5 m high while the main Maspalomas slipface was 2.2 m high. The shorter height of the Maspalomas slipface would shorten the duration of grainflows.

The Maspalomas dune had a higher frequency of grainflow activity (Table 2), occurring on average every minute whereas Breton et al. (2008) observed an average recurrence of 2.7 minutes. Wind measurements in Breton et al., were collected at a height of 0.5 m and ranged between 7.38 and 7.49 m s\(^{-1}\). Adjusting the average Maspalomas wind speed of 9.5 m s\(^{-1}\) from a height of 1 m to a height of 0.5 m using the wind profile power law results in a velocity of 8.6 m s\(^{-1}\). The higher frequency of grainflow activity at Maspalomas is likely due to the greater wind speeds at the study site. Greater wind velocities trigger grainflows more frequently due to the larger amounts of sediment delivered to the slipface. Ignoring ‘slab’ flows, which do not appear to have occurred during the Breton et al. (2008) study, the spatial area of the Maspalomas grainflows was on average about 2 m\(^2\) smaller. This difference may also be due to the dune height where taller dunes produce greater planform areas of grainflows as they flow downslope.

Nield et al. (2017) collected data on a 5.12 m high dune using a Terrestrial Laser Scanner with wind measurements from anemometers at a height of 0.5 m over two days
of observation. Differing grainflow behavior was observed and related to wind velocity, where lower wind velocities (<6 m s\(^{-1}\)) resulted in small, discrete failures that occurred near the dune brink with limited grainflow lengths and thicknesses (Nield et al., 2017). Moderate winds (~6.5 m s\(^{-1}\)) produced grainflow activity further downslope of the dune brink with the ability to transport sediment to the bottom of the slipface. Strong winds (>8.4 m s\(^{-1}\)) enabled ‘multiple families of failures’, where larger grainflows initiated near the top of the slipface and smaller grainflows occurred partway down the slope (Nield et al., 2017). Under strong winds, there was frequent grainflow activity and the grainflows that occurred had longer and thicker tongues of sediment that successfully transported sediment to the bottom of the slipface (Nield et al., 2017). Data also show that there was a downslope shift in the location from the dune brink of larger grainflow initiation points (location of failure) from 30 cm during wind velocities around 6 m s\(^{-1}\) to 40 cm for velocities > 6 m s\(^{-1}\) with some grainflows initiating 1 meter below the dune crest (Nield et al., 2017).

While the Maspalomas observations did not include a study of grainflow behavior under a variety of wind conditions, the data agree well with the behavior observed by Nield et al. (2017) during stronger wind velocities. The wind velocity at the study site, adjusted to a height of 0.5 m, was approximately 8.6 m s\(^{-1}\) and exhibited a high frequency of grainflow activity, where some grainflows occurred simultaneously or shortly after one another, or in ‘multiple families of failures’. No downslope shift was detected for the initiation point of ‘hourglass’ grainflows, where the location of failure remained around 30 cm below the dune brink but many ‘lobes’ and ‘funnels’ initiated
further downslope. Additional observations need to be made to determine if the downslope shift in grainflow failure is directly linked to wind velocity alone or if slipface length and dune morphology may have an effect. More specifically, an investigation of the conditions that produce sediment bulges (e.g. Allen, 1968; Allen, 1970; Hunter, 1985; Anderson, 1988; Walker and Nickling, 2002; Kok et al., 2012; Sutton, 2012; Sutton et al., 2013a,b) near the dune brink as opposed to larger sediment wedges (e.g. Nickling et al., 2002; Cupp et al., 2005; Nield et al., 2017) may be helpful in elucidating this difference in observation.

2.5 Conclusion

Using a combination of high resolution, ground-based continuous laser scans and simultaneous video recordings, various grainflow morphologies are presented for the first time. This study includes precise measurements of grainflow thickness as well as area and volume estimates of redistributed sediment for each grainflow morphology observed (Table 1). Typical grainflow thicknesses ranged from about 0.05 to 8 cm, where the thicker portions of grainflows were located where sediment accumulated at the bottom of the slipface. On average, grainflows were approximately 1 cm thick. ‘Slab’ flows were responsible for redistributing significant amounts of sediment, averaging about 182,111 cm³ per event but were not as common as ‘hourglass’ grainflow morphologies and ‘funnel’ or ‘lobe’ flows. ‘Hourglass’ grainflows redistributed an average of 22,494 cm³ per flow event while ‘funnels’ and ‘lobes’ redistributed an average of 1,312 and 1,944 cm³, respectively.
The high-resolution measurements of grainflow characteristics presented herein will be vital in verifying and improving laboratory and modelling efforts to identify grainflow triggers for morphologically diverse grainflow events and sediment volume flux in aeolian environments. With the growing literature on aeolian slipface processes, there is a need for a classification of lee slope grainflows based on formation patterns (e.g. flow area, frequency and duration) and morphology. The morphology classification presented in this study provides a foundation for future study and a structure to support discrete observations between different aeolian environments. For example, additional research is needed to investigate how grainflow style is affected in coastal and polar environments in contrast to arid environments where cohesion from salts, liquid water and ice may affect grainflow behavior. This classification will aid in distinguishing the influences on specific styles of flows which can be later linked to controlling parameters such as wind strength and direction, turbulent airflow, sediment deposition, grain texture, and environmental influences. This will ultimately lead to a better interpretation of aeolian strata and paleo environments of dunes preserved in the rock record (e.g. estimates of dune height; McKee et al., 1971; McKee and Bigarella, 1972; Morris et al., 1972; Bigarella, 1975; Hunter, 1977; Kocurek and Dott, 1981; Sweet et al., 1988; Sweet and Kocurek, 1990; Cooke et al., 1993; Bourke, 2005; Anderson and Walker, 2006; Eastwood et al., 2012) as well as a better understanding of the intricacies of slipface processes and overall dune migration.
Acknowledgements.

We would like to thank Luis Hernandez for local logistical help in Maspalomas, the dedicated field assistants from the Universidad de Las Palmas de Gran Canaria, the cartographers who recorded GPS points, Dave Rogers for training and technical help with the FARO laser scanner and SCENE software, Stephen Sutton and other anonymous reviewers of this paper who provided many helpful suggestions and insights. This research was funded through a Vice-Chancellor’s Research Scholarship from Ulster University and is a contribution towards NERC grant number NE/F019483/1.

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CHAPTER 3

Aeolian Slipface Dynamics and Grainflow Morphologies on Earth and Mars

Icarus, accepted

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Abstract

In 2015, an active dune field on Mars was visited by the Curiosity rover in Gale Crater providing the first high resolution ground images of fine scale windblown features not previously resolved from orbital-based imagery. For the first time, these images allow for direct comparison with terrestrial aeolian dynamics and provide critical ground truth data to bridge the gap between model predictions and satellite observations. The image data from the slipface on the Namib dune within the Bagnold dune field shows grainflow morphologies that are similar to dunes on Earth. Quantitative estimates of flow thickness, based on shadow length are presented for the grainflows on the Namib dune slipface and compared to grainflow characteristics measured by terrestrial laser scans from the Maspalomas dune field located in Gran Canaria, Spain. Using observations from Maspalomas to support interpretations of martian slipface dynamics, we discuss implications for the local wind regime, style of grainflow, seasonal activity, and dune migration. The presence of multiple large-magnitude grainflows on the Namib slipface suggests an active aeolian environment, capable of delivering enough sediment to the slipface to initiate these flows and transport sediment to the bottom of the lee slope. However, the thinness of grainflows on the Namib dune, the formation of smaller grainflows directly below the dune brink and limited grainfall suggest a lower wind energy environment, at least for the most recent slipface activity. Large, actively migrating stoss ripples obliquely oriented to the dune crest regularly deposit sediment on to the upper slipface and may be a mechanism in which larger grainflow occur during seemingly low energy wind events. This mechanism of sediment delivery may also explain the existence of a variety of slipface
morphologies, both young and old, which are otherwise quickly erased on Earth due to sediment redistribution and grainfall.

3.1 Introduction

The surface of Mars is dominated by aeolian processes which have operated effectively over billions of years. In the absence of in situ observation, studies on martian dune dynamics have relied on atmospheric modelling (e.g. Anderson et al., 1999; Fenton et al., 2005; Hayward et al., 2009; Jackson et al., 2015) and high-resolution satellite images to analyze morphology, and record change (e.g. Fenton et al., 2005; Fenton, 2006; Bridges et al., 2007; Hayward et al., 2007; Bourke et al., 2008; Hayward et al., 2009; Hobbs et al., 2010; Silvestro et al., 2010; Bridges et al., 2011; Silvestro et al., 2011; Bridges et al., 2013; Silvestro et al., 2013; Cardinale et al., 2012; Cardinale et al., 2016). Through the careful analysis of annual ripple migration and multiple years of repeat High Resolution Imaging Science Experiment (HiRISE) images from the Mars Reconnaissance Orbiter, estimates of dune migration rates have been determined for various dune fields on Mars and range from 0.1 to 12 m/ Mars year (Bridges et al., 2007; Bourke et al., 2008; Silvestro et al., 2010; Bridges et al., 2011; Chojnacki et al., 2011; Hansen et al., 2011; Silvestro et al., 2011; Bridges et al., 2012a, b; Bridges et al., 2013; Geissler et al., 2013; Silvestro et al., 2013; Chojnacki et al., 2015; Cardinale et al., 2016; Runyon et al., 2017). Mars dunes generally migrate at a slower rate than most terrestrial dunes of similar morphology (e.g. Finkel, 1959; Long and Sharp, 1964; Hastenrath, 1967; Pye and Tsoar, 1990; Jimenez et al., 1999; Dong et al., 2000; Vermeesch and Drake, 2008) but are comparable to some small dome and barchan dunes having migration rates between 4 and 8 m/Earth year (Dong et al., 2000;
Bristow and Lancaster, 2004) as well as dunes found in Antarctica, having migration rates of about 1.5 m/Earth year (Bourke et al., 2009).

Dune migration is largely accomplished through a series of individual grainflows that transport sediment from the stoss slope to the bottom of the lee slope, advancing the slipface. In addition, grainflow formation patterns, morphology, and frequency reflect characteristics of the environment in which they occur such as wind velocity, sediment properties, and climate (e.g. Allen, 1968, Allen, 1970; McKee and Bigarella, 1972; Morris et al., 1972; Sweet and Kocurek, 1990; McDonald and Anderson, 1992; McDonald and Anderson, 1995; McDonald and Anderson, 1996; Nickling et al., 2002; Cupp et al., 2005; Breton et al., 2008; Sutton, 2012; Sutton et al., 2013a,b; Pelletier et al., 2015; Nield et al., 2017; Cornwall et al., 2018). Therefore, the study of grainflows is an integral part of dune dynamics and climate interpretation.

Excluding the largest of grainflows, it is nearly impossible to discern details of slipface activity on Mars from HiRISE satellite images which have a resolution of 25 cm/pixel. The Curiosity rover provided the first high resolution ground images of an active dune slipface on the Namib dune in the Bagnold dune field in Gale Crater (Fig. 1) opening a unique opportunity for a more detailed study of aeolian features on Mars. For the first time, these images allow for a direct comparison between terrestrial slipface processes and those currently in operation on Mars.
Figure 1. Top: CTX/HRSC/Viking composite mosaic showing the location of the Namib dune on Mars (black rectangle below the Curiosity landing site oval) in relation to the Bagnold dune field. Bottom: HiRISE image ESP_044172_1755 of the Namib dune and neighbouring High dune with the Curiosity rover in front of the Namib dune slipface. Dashed lines on the Namib dune are the approximate extents of the western central, and eastern portions of the slipface shown in Figures 2, 3, and 4, respectively.
3.1.1 Grainflow Formation

Terrestrial studies have reported mechanisms for slipface grainflow initiation that include localized over-steepening, slump degeneration, destabilization from larger grainflows or disturbance of a mid-slope ‘lock up zone’, and complex airflow patterns. Localized over-steepening of the lee slope typically occurs tens of centimeters below the dune brink where saltating grains of sediment are deposited from the stoss slope (e.g. Allen, 1968; Allen, 1970; Borowka, 1979; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1992; McDonald and Anderson, 1995; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005; Kok et al., 2012; Sutton, 2012; Sutton et al., 2013a,b). When the deposited sediment exceeds the critical angle of repose of the grains, failure occurs, forming an alcove that spreads laterally upslope toward the dune brink and a depositional lobe of sediment that spreads laterally downslope and accumulates below the alcove (e.g. Allen, 1968; Allen, 1970; Hunter, 1977; Borowka, 1979; Fryberger and Schenk, 1981; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1992; McDonald and Anderson, 1995; Tischer et al., 2001; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005; Dasgupta and Manna, 2011; Kok et al., 2012; Sutton, 2012; Sutton et al., 2013a,b; Cornwall et al., 2018; Nield et al., 2017).

Slump degeneration was first described by Fryberger and Schenk (1981) as an alternative to the grainflows that formed alcoves. During wind tunnel experiments, these alternative grainflows were observed to initiate as a series of tensional features near the top of the slipface. As the flow progressed, compressional features (folds) formed in places where the sediment slowed and overrode parts of the flow, resulting in a ‘slump sheet’ of sediment with minor deformational structures in cross-section, suggesting a form of dry cohesion (Fryberger
and Schenk, 1981). Slump degeneration has not been studied in depth but may also have been observed by Sutton (2013b) as small non-cohesive slabs or larger features (meters across), termed slab flows as well as in the coastal dunes of the Maspalomas dune field (Cornwall et al., 2018). It is unknown what caused the dry cohesion observed by Fryberger and Schenk (1981) but during field observation, it is probable that cohesion of dune sediment may arise with the presence of moisture (liquid or ice) in the subsurface sediment layers or due to induration from soluble salts.

Smaller grainflows may initiate due to disturbances from larger grainflow activity (Breton et al., 2008; Cornwall et al., 2018) or from the destabilization of the mid slipface slope in a region where suspended sediment settles, creating a secondary location of localized over-steepening (McDonald and Anderson, 1992; McDonald and Anderson, 1995’ McDonald and Anderson, 1996; Nickling et al., 2002; Nield et al., 2017). The accumulation and over-steepening of sediment mid slope may also be enhanced by grainflows that did not successfully deliver sediment to the base of the slipface. Sediment transport from these flows is halted in a ‘lock up zone’, partway down the slipface where sediment from other smaller grainflows also accumulates (McDonald and Anderson, 1992; 1995; 1996).

The role of airflow on the lee side of a dune may also influence grainflow activity, where secondary air flow patterns generated by flow separation at the dune crest and the subsequent reattachment flow may produce complex eddies and vortices (Parsons et al., 2004a,b; Jackson et al., 2013a,b; Smith et al., 2017). Though not well understood, these secondary flow patterns may have a significant impact on surface shear stress, resulting in sediment redistribution on the slipface (e.g. Wiggs, 2001; Nickling et al., 2002; Walker and Nickling, 2002; Cupp et al., 2005).
For example, incident airflow oriented between 25° to 90° to the slipface on a dune may produce deflected flow on the slipface in the form of 2D eddies and 3D vortices (Sweet and Kocurek, 1990; Eastwood et al., 2012) resulting in lateral transport of sediment (Walker, 1999).

In addition, greater wind velocities have been shown to decrease the angle of initial yield, resulting in grainflow activity at lower critical angles than otherwise possible (Pelletier et al., 2015).

3.1.2 Comparing Terrestrial Grainflow Activity to Mars

Terrestrial dunes are highly dynamic and under wind conditions conducive to grainflow activity, relict structures such as ripples and older grainflows are quickly erased by grainfall or redistribution of sediment (e.g. Bagnold, 1941; Allen, 1970; Hunter, 1977; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1995; Kok et al., 2012; Cornwall et al., 2018). Martian aeolian dynamics operate under significantly thinner atmospheric conditions compared to Earth (<~1.7% of Earth’s surface atmospheric density) and lower surface gravity about 38% of Earth’s gravity (Bridges et al., 2017). The fluid threshold of grain saltation therefore requires much greater wind speeds compared to Earth. Lander measurements and atmospheric circulation models have indicated that these above-threshold speeds are rare, contradicting observations of sand-sized particles moving across the planet surface (Zurek et al., 1992; Sullivan et al., 2000; Haberle et al., 2003; Fenton et al., 2005). However, sand saltation may be possible at lower wind speeds through the development of saltation clusters via self-sustaining saltation trajectories from grains that are sporadically mobilized due to a passing eddy (Sullivan & Kok, 2017). Once a grain is in motion, it is easier to maintain saltation on the martian surface.
Due to the lower gravity and vertical drag, saltating grains have higher and longer trajectories (Almeida et al., 2008; Kok, 2010; Kok et al., 2012). Grains are airborne for a longer period of time resulting in a prolonged acceleration by wind which produces an impact threshold comparable to terrestrial values, thus capable of setting other grains in motion upon collision (Claudin and Andreotti, 2006; Almeida et al., 2008; Kok, 2010a,b).

A variety of aeolian structures related to grain saltation are visible on the Namib dune on Mars. The stoss slope features two scales of ripples, where the smaller bedforms, identified as impact ripples, are superimposed on top of large ripples with an average wavelength of about two meters (Lapotre et al., 2016). The large ripples form a ladder back pattern, where the ripple crestlines are oriented NW and NE (Silvestro et al., 2013; Lapotre et al., 2016) and intersect the barchan dune brink obliquely along the horns and transverse in the center (Ewing et al., 2017). There are two slipface surfaces present on the Namib dune, where the primary slipface faces toward the south and the secondary slipface is located along the western flank of the dune (Ewing et al., 2017). The primary slipface of the Namib dune is complex, having a mixture of a series of overlapping older and younger grainflows with indications of slumping, little evidence of widespread grainfall, and ongoing impact ripple formation (Ewing et al., 2017).

In general, grainflow processes dominate the central portion of the primary slipface while impact ripple formation, parallel to the slipface, and grainfall deposits dominate the horn slipface slopes (Ewing et al., 2017). The secondary slipface is dominated by large ripples that migrate obliquely downslope toward the south and intersects with the western horn of the dune (Ewing et al., 2017).
Mars experiences seasonal cycles of aeolian activity and inactivity, where the southern winter solstice is a quiet period with limited ripple movement and infrequent grainflows (e.g. Ayoub et al., 2014; Hansen et al., 2011; Bridges et al., 2017). During this time, grain movement is most likely driven by periodic gusts of wind and any activity that occurs is sporadic (Bridges et al., 2017). In the absence of dynamic observations and an opportunity to revisit the Namib dune throughout the martian year, the flow morphology and location of these grainflow events may have preserved information about the latest grainflow event and the aeolian conditions that produced them.

We investigate the differences and similarities of terrestrial and martian slipface dynamics using a dune in the Maspalomas dune field in Gran Canaria, Spain as an analog to the grainflow activity preserved on the Namib dune slipface in Gale crater, Mars (Fig. 2, 3, 4, and 5). This study applies the classification scheme of grainflow morphologies proposed by Cornwall et al. (2018; Fig. 6) to Mars grainflows and an interpretation of the local wind regime responsible for the most recent grainflow activity, is presented, supported by terrestrial field observations of grainflow morphodynamics. Estimates of the grainflow thickness of the freshest flows on the Namib slipface and volumes calculations are provided for each grainflow and compared to grainflow thicknesses and volumes measured in the Maspalomas dune field, Gran Canaria, Spain. Estimates of flow volume provide an indication of the effectiveness of slipface processes on the Namib dune for the most recent grainflow activity and may also provide some insights into dune migration patterns in the Bagnold dune field. Lastly, we discuss the factors that influence grainflow initiation and their formation patterns as well as implications for seasonal slipface activity and dune migration.
Figure 2. Right-hand side (eastern horn) of the Namib dune lee slope showing multiple grainflows, ripples, and some grainfall deposits with the Curiosity rover in the foreground. Image is mosaic of 23 images taken by the mast-mounted Left Navigation Camera (Navcam) on December 18, 2015 (mission Sol 1196), providing a 360-degree cylindrical-perspective projection panorama centred at 125 degrees azimuth. Local mean solar time for image exposures was 4 PM. ‘GF’ signifies grainfall and ‘HG’ signifies hourglass grainflow.
Figure 3. Same as Figure 2 but for the central portion of the Namib dune slipface. This section of the slipface contains the freshest grainflows, well-defined ripples and very little evidence of rainfall. Dashed lines represent the boundaries of the mapped portion of the slipface in Figure 5.
Figure 4. Same as Figure 2 but for the left-hand side (western horn) or the Namib dune slipface. Multiple grainflows can be seen and there is evidence of grainfall along the upper lee slope.
Figure 5. Map of the grainflow morphology and slipface activity on the Namib dune of the Curiosity mission on Mars (A). Mapped morphologies include: tensional cracks (yellow), ripples (blue), hourglass-shaped grainflows (red), and secondary grainflows (magenta), where lobes are labeled with ‘L’ and funnels ‘F’ and correlate to the labels in Table 1. The two hourglass flows shown in (A) correlate with flows H1 and H2 in Figure 4. Panels B-D show magnifications of some of the secondary flows identified on the slipface. Panels B and C show details of lobe flows and panel D shows a funnel flow. Mapping was done in ArcMap 10.3.1. Namib dune slipface image was taken December 17, 2015 (sol 1200) using the Curiosity’s Mast Camera telephoto-lens camera. Image was taken about 7 m from the camera and the dune height is approximately 5 m.
Figure 6. Grainflow morphologies identified in the Maspalomas dune field, Gran Canaria, Spain, including hourglass grainflows accompanied by the formation of an alcove, smaller funnel and lobe flows, and slab flows that affect large areas of an entire slipface. The checkered A4 paper (21 x 29.7 cm) on target board at the crest of the dune was used for GPS registration and can be used for background scale of the slipface. A foreground scale is provided. Slipface height is approximately 2.2 meters.
Grainflows on Earth have been the key to understanding aeolianites and paleoenvironments (McKee et al., 1971; McKee and Bigarella, 1972; Morris et al., 1972; Bigarella, 1975; Hunter, 1977; Bourke, 2005; Grotzinger et al., 2005; Eastwood et al., 2012). In a similar fashion, the aeolian record on Mars potentially contains valuable insights into the geologic history of the planet, aiding in the interpretation of martian aeolianites such as those found at Meridiani Planum (Grotzinger et al., 2005) or the cross-bedded sandstone of the Stimson formation; part of the basal flank of Aeolis Mons (aka Mount Sharp) in Gale Crater, Mars (Banham et al., 2018).

3.2 Methodology

3.2.1 Earth and Mars Study Sites

*Earth and Mars Study Sites.* The Maspalomas study site (27.744° N, -15.573° W) is used as an analog to the martian Namib dune slipface features (-4.686° N, 222.364° W) and is described in detail in Cornwall et al. (2018) and Jackson et al. (2013b). The Maspalomas dune field was chosen for an analog because the dry climate, having <100mm/year precipitation (Marzol, 1987), with sparse vegetation growth, and regular slipface activity, made it a convenient location to study the morphometrics of typical arid dune grainflows. We apply the classification of grainflow morphologies from Cornwall et al. (2018) including hourglass, slab, lobe and funnel flows to the grainflow activity on the Namib dune (Fig. 5a) imaged by the Mars Curiosity rover. The Maspalomas slipface observations were collected on a portion of a transverse dune, having a height of 2.2 m with a slipface angle of 32.15° (Cornwall et al., 2018).
The Namib dune is a barchan dune having a height of about 4 m and an average slipface slope of 29° with the slope exceeding 35° in a few locations (Ewing et al., 2017).

Grain sizes collected in the Maspalomas dune field study site ranged from 136 to 522 µm, averaging 244 µm (Cornwall et al., 2018), and were composed of biogenic marine materials (Hernandez et al., 2002) and phonolitic rocks (Martinez, 1986). Sediments from the Namib dune are mafic with the most abundant crystalline phases being plagioclase, olivine and pyroxenes as well as a large component of amorphous material (Bridges et al., 2016; Achilles et al., 2017; Cousin et al., 2017; Ehlmann et al., 2017; Johnson et al., 2017; Lapotre et al., 2017; O’Connell-Cooper et al., 2017). The median grain size of the Namib dune sediments was much finer than the sand grains in Maspalomas and ranged from 100 to 150 µm, or very fine sand (Ewing et al., 2017; Sullivan and Kok, 2017) with a few isolated coarser grains (Ehlmann et al., 2017).

3.2.2 Wind Regime

Figure 7 shows a comparison of an Earth year of available wind data (from February through September) collected near the Maspalomas study site (Cornwall et al., 2018) and wind data from the Curiosity rover in Gale Crater, Mars. Wind data for the Maspalomas dune field was collected by the Playa del Ingles meteorology station approximately 450 m southeast from the study site at a height of 3 m. Gale Crater wind data, collected by the Rover Environmental Monitoring Station (REMS; Gomez-Elvira et al., 2012) Mars Science Laboratory (MSL) Curiosity mission at a height of 1.5 m was retrieved from the Planetary Data System (PDS) website. Wind data was taken from sols 884 to 1485 of the Curiosity Mission to overlap with observations at the Namib dune.
Figure 7. Wind Regime for the Maspalomas dune field (top) and Gale Crater, Mars (bottom). Data displayed shows seasonal wind patterns at Maspalomas, Gran Canaria, Spain from February – September 2015 and Curiosity REMS wind data for sols 884 – 1485. REMS data was collected along Curiosity’s traverse and therefore may include some wind variability due to nearby topographic influences but the general N-S bimodal trend agrees well with mesoscale modelling (e.g. Pla-Garcia et al., 2016). Solid lines represent the orientation of the dune slipface. The dashed line represents the orientation of the large ripples on the stoss slope of the Namib dune. Ripples on the Maspalomas dune were oriented parallel to the slipface.
An entire Mars year of wind data centered on the Curiosity rover’s visit to the Namib dune was originally planned to be included but some measurements were unreliable or nonexistent and no data was collected after sol 1485. As a result, there are about 86 sols out of one martian year (687 sols) that are not displayed.

The REMS data is treated with caution as the loss of one of the two wind sensors on the rover made reliable determination of wind speed and direction difficult (Pla-Garcia et al., 2016). In addition, wind data was collected throughout Curiosity’s traverse and daily variations may reflect influences from local topography especially as the rover approached Mount Sharp. To ensure more reliable wind sampling was used in this study, Mars wind data was restricted by the wind sensor confidence level for every sol. Observations with weakened data reliability due to temperatures <\(-50^\circ\text{C}\), electronic noise, rover movement, incorrect wind sensor configuration, and rear wind direction were excluded. Despite the uncertainties introduced by sensor limitations and changing topography, we are confident in using REMS wind data to compare the wind regime of the Maspalomas study site to Gale crater because the derived wind directions from REMS have shown good agreement with the Mars Regional Atmospheric Modelling System (MRAMS; Pla-Garcia et al., 2016) and the Mars Weather Research and Forecasting (WRF) numerical model (Newman et al., 2017). However, there remain discrepancies between wind velocity measurements from the rover and model predictions but these differences may, in part, be due to complex airflow patterns from local topography not resolved by the models (Pla-Garcia et al., 2016; Newman et al., 2017). Velocity measurements from the rover are valuable in this study because the complex airflow patterns that affect wind speed are
unresolved by mesoscale models. These near surface wind speeds are responsible for sediment transport at the dune scale and constrain periods of grainflow activity on the Namib dune.

3.2.3 Mars Grainflow Thickness

Measurements of Maspalomas grainflow characteristics were collected using a high-resolution ground-based terrestrial laser scanner (TLS; Cornwall et al., 2018). Spatial estimates of grainflow width, length and area of a couple flows on the primary Namib slipface were previously made by Ewing et al. (2017). This study builds upon these measurements by estimating grainflow thickness and calculating the volume of redistributed sediment for the freshest grainflows on a portion of the Namib slipface. In the absence of data (i.e. Mastcam DEMs) that can resolve grainflow thickness on the Namib dune, flow thickness and subsequent volume estimates for the Namib slipface were trigonometrically estimated using shadow length and the sun’s elevation (Table 1; Curran, 1985). If the sun geometry is known, shadow lengths can be utilized to estimate the heights of the objects that cast them in two dimensional images. This a common spatial analysis technique practiced in remote sensing, specifically with high resolution satellite images (e.g. Huertas and Nevatia, 1988; Liow and Pavlidis, 1990; Shettigara and Sumerling, 1998). In a similar fashion, this technique is used for the shadows cast by grainflows on the slipface of the Namib dune, using Mastcam images 1200ML0054960060503183C00_DXXX and 1200ML0054960130503190C00_DXXX.
Table 1. Comparison of dune slope and grainflow properties for Earth and Mars recorded in centimeter units. Values in parentheses are the standard deviations for each averaged grainflow morphology. For initiation point, ‘U’ represents undefined, where the original location of initiation could not be determined. Averaged values are presented for the Maspalomas dune field grainflows from Cornwall et al. (2018). Thickness estimates for the two Namib dune hourglass grainflows were trigonometrically measured using shadow length and the sun’s elevation at the time of observation. Average slope for the Namib dune, grainflow length and width was reported by Ewing et al. (2017). The measured hourglass grainflows on the Namib dune are shown in Figure 5.

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<tr>
<td>Hourglass 1 U</td>
<td>0.189</td>
<td>0.328</td>
</tr>
<tr>
<td>Hourglass 2 U</td>
<td>0.328</td>
<td>1.415</td>
</tr>
</tbody>
</table>
The sun’s elevation for each image was approximately 51.63° and 51.93° at the time the images were acquired at 12:18 and 12:20 LMST, respectively. Grainflow thickness was thus calculated by:

\[ T = (\text{Shadow Length}) \times \tan(\text{Sun Elevation}) \]

Only the freshest of grainflows cast a significant enough shadow to be measured and so thickness measurements were limited to the most recent grainflow activity.

Since the Mastcam images were not orthorectified in this study, foreshortening of the Mastcam image mosaic was accounted for using a spatial analysis technique involving perspective distortion to derive reliable estimates of grainflow shadows at particular locations on the dune. Perspective distortion occurs when there is a relative scale of nearby and distant features in a two-dimensional image, such as the base of the Namib dune and the brink. Perspective distortion is linear and dependent on distance. Therefore, knowing the distance of the Curiosity rover from the dune (~15 m) and the approximate height of the Namib dune, a focal length can be determined at any point on the dune slipface (e.g. brink or mid slope) with an adjusted pixel scale for the features being measured (Fig. 8).

To assess the accuracy of our pixel-scale correction based on focal length, we compared our estimates with measurements from the Mastcam DEM of Ewing et al. (2017). Using our technique, the two grainflows from Figure 5 were measured. We estimated a scarp width of 58 cm (vs. 54 cm from the DEM) and a lobe width of 60 cm (vs. 57 cm from the DEM) for the smaller grainflow, and a scarp width of 64 cm (vs. 67 cm from the DEM) and a lobe width of 65 cm (vs. 66 cm from the DEM) for the larger grainflow.
The two measurements appear to be in good agreement and measurements of grainflow shadows are considered reliable estimates. Measurement estimates of grainflow length were not attempted for the larger grainflows using an adjusted resolution based on perspective because the vertical resolution changes dramatically down the slope of the slipface.

Measurements of area for smaller grainflows near the dune brink were collected, where changes in vertical resolution were minimal. In addition, measurements were restricted to the central portion of the slipface where measurements were the most reliable and image distortion from perspective angles and curvature of the dune limbs were minimal.

The reliability of the grainflow thickness estimates for Mars were additionally tested by conducting a similar calculation for the observations from Maspalomas and comparing the derived measurements to TLS data. The trigonometrically-derived thicknesses for base grainflow thickness in Maspalomas were within ± 0.30 cm of the values recorded by TLS which
accurately recorded grainflow attributes on the submillimeter-scale (Cornwall et al., 2018).

Grainflow areas of the smaller grainflows in Table 1 and Figure 5 were calculated using ArcMap and sediment volume estimates for each grainflow were determined using the volume of a wedge to approximate the thickening of a grainflow downslope, following the convention of Cornwall et al. (2018).

3.3 Results

The Maspalomas dune slipface in Gran Canaria, Spain and the Namib dune slipface on Mars have many similarities in regards to grainflow morphology. Both slipfaces displayed hourglass grainflows as well as smaller lobe and funnel flows. However, there were minor morphometric differences.

3.3.1 Hourglass Grainflows

Measurements were performed on the two freshest hourglass grainflows on the Namib dune (Fig. 3 and 5). These grainflows were larger than the Maspalomas hourglass grainflows in area but thinner in flow thickness (Table 1). The estimated Namib hourglass grainflow areas were approximately 16,500cm$^2$ and 39,600cm$^2$ and the average area for Maspalomas grainflows was approximately 11,000 cm$^2$ (Table 1; Fig. 9). The deposit thickness at the base of the grainflow for both Namib hourglass flows was below the average for those observed in Maspalomas by more than 1 cm (Table 1; Cornwall et al., 2018). The larger Namib dune hourglass flow had a volume estimate of approximately 7,300 cm$^3$, significantly below the
terrestrial average observed in Maspalomas (~22,000cm$^3$), despite having a larger planform area (Fig. 9).

3.3.2 Lobe and Funnel Grainflows

Lobe and funnel grainflows were a frequent occurrence on the Maspalomas dune slipface, forming on average every minute, and tended to initiate mid-slope (Cornwall et al., 2018). Based on these field observations, the occurrence of small grainflows on the primary Namib slipface was significantly less than expected, where only a few lobe and funnel flows could be identified on the central portion of the slipface (Fig. 5). In contrast to Maspalomas observations, lobe and funnel grainflow activity on the Namib dune favored initiation near the dune brink (Fig. 5a, b and d), almost completely independent from disturbances from hourglass

Figure 9. Mars (red) and Maspalomas (blue) grainflow estimations of area vs volume on log-log axes. Hourglass flows are shown as triangles, lobe and funnel flows are shown as circles, and slab flows are shown as boxes.
flows apart from one small lobe flow (Fig. 5c). Funnel grainflows were extremely rare. Only one was identified on the portion of the Namib slipface that was mapped (Fig. 5a and d). In contrast to some of the lobe and funnel grainflows observed on the Maspalomas slipface, none of the smaller Namib grainflows identified in this study successfully transported sediment to the base of the slipface. Outside the primary slipface, a number of smaller grainflows were identified on the lee slopes of large ripples migrating obliquely to the secondary slipface along the western flank of the Namib dune (Lapotre et al., 2016; Ewing et al., 2017).

Of the freshest lobe and funnel flows on the Namib, grainflow area ranged between 51 and 580 cm$^2$, smaller than the typical Maspalomas lobe and funnel flows (Table 1, Fig. 9). In addition, the small grainflows on the Namib dune primary slipface were also significantly thinner than their terrestrial counterparts, where Maspalomas lobe and funnel flows averaged about a 1 cm thickness while the Namib flows averaged approximately 0.37 cm (Table 1; Fig. 9).

3.3.3 Tensional Cracks

Multiple tensional cracks were identified on the surface of the Namib slipface (yellow lines; Fig. 5a). Similar generally horizontal tensional cracks were observed on the Maspalomas slipface but these features always preceded a slab flow (Cornwall et al., 2018; Fig. 10). Slab flows initiated centimeters below the dune brink and affected large areas (typically meters across) of the slipface and moved large volumes of sediment (Table 1; Fig. 9) compared to hourglass and lobe or funnel grainflows. The tensional cracks on the Namib slipface are pervasive in a region where there appears to be a slump feature or separation of sediment from the dune brink (Fig. 3 and Fig. 5a and b).
Figure 10. Formation of a slab flow (top) in the Maspalomas dune field, Gran Canaria, Spain. Early stage slab flow formation begins as a series of horizontal tensional cracks a few centimetres below the dune crest shortly followed by sediment flow downslope. Late stage slab flow (bottom) contains multiple compression folds as well as tensional cracks throughout the flow surface. Secondary grainflow may also be initiated due to nearby slope destabilization such as the hourglass flow on the left. The time lapse between the early stage and late stage slab flow images is 11 seconds. Two scale bars are given to account for perspective.
On a much smaller scale, tensional cracks and slump features also appeared to be present on the downwind slopes of the large stoss ripples on the Namib dune (Ewing et al., 2017) and may have a similar formation mechanism to the slab flows observed on the Maspalomas dune slipface.

3.4. Discussion

The Namib dune slipface contains an assemblage of aeolian structures bearing a record of the most recent slipface activity. Fresh grainflows have obscured underlying lee slope ripples within the central portion of the barchan slipface while older grainflows are mantled in ripples (Fig. 3 and 5). Evidence of rainfall is scarce in this region of the slipface but more pronounced along the lee slope of the horns (Fig. 2 and 4). Curiosity imaged the Namib dune slipface in late autumn and HiRISE images overlapping with the Curiosity mission indicate that the autumn and winter seasons were a time of little to no slipface advancement for the Namib dune (Bridges et al., 2017). Observations from the rover confirmed there was little grain movement (Bridges et al., 2017) suggesting that any significant grain transport may entirely cease during the autumn and winter seasons. During the summer, the primary wind direction, according to REMS data, ranges from east to south-southwest (Bridges et al., 2017; Newman et al., 2017; Fig. 1 and Fig. 7). These winds would be incident to the Namib dune slipface, unfavorable to widespread rainfall generation but potentially conducive to ripple formation and migration on the lee slope as well as the stoss slope (Ewing et al., 2017). Summer, therefore, may be a season of pronounced ripple migration and activation of the secondary slipface along the western flank of the Namib dune. A closer inspection of the patterns of grainflow activity provide more
information concerning the aeolian conditions that produced the features on the preserved on the primary and secondary slipface slopes.

3.4.1 Sediment Flux and Wind Regime

Sediment delivery onto the slipface of a terrestrial dune is largely driven by rainfall, including saltating grains over the dune brink and finer-grained sediment settling further down slope. Patterns of slope failure can be identified within zones on the slipface (e.g. Hunter, 1985; McDonald and Anderson, 1995; Nickling et al., 2002; Sutton et al., 2013a,b; Nield et al., 2017). On terrestrial dunes, there exists a relationship between wind velocity and the location, frequency, and magnitude of grainflows on a slipface. Nield et al. (2017) reported the delivery of sediment to the base of the slipface, where during strong winds (>6 m s⁻¹), a higher number of grainflows occurred, sometimes in clusters of activity, and the grainflows tended to be larger in magnitude in regards to redistributed sediment volume and areal extent. As wind velocities increased, grainflows became capable of delivering sediment to the base of the slipface, thus contributing to the overall advancement the slipface (Nield et al., 2017).

In addition, Nield et al. (2017) observed that larger grainflows initiated at the top of the slipface while smaller grainflows occurred partway down the slipface at greater wind velocities whereas during weaker winds (<6 m s⁻¹), slipface activity consisted of small, thin, discrete grainflows initiating near the brink with a limited depositional lobe. Observations from the Maspalomas dune field supported these findings (Cornwall et al., 2018) and it is possible that this response also occurs in the Martian environment with wind speeds being adjusted appropriately for Mars atmospheric conditions.
The Namib slipface displays a series of relatively evenly spaced hourglass grainflows with limited occurrences of lobes and funnels (Fig. 2, 3, 4 and 5). Lobes and funnels did not form as regularly on the Namib dune, compared to observations from Maspalomas, based on their lack of preservation. The lobes and funnels that were identified on the Namib slipface preferentially occurred immediately below the dune brink and were relatively thin, suggesting limited sediment input on to the slipface and a lower frequency of effective wind velocities. Maspalomas lobe and funnel flows were often observed to precede larger hourglass flows (Cornwall et al., 2018). Therefore, it is likely that some lobe and funnel flows were obscured by the larger hourglass grainflows on the Namib dune. However, the lack of evidence of lobe and funnel flows following large grainflows and the concentration of these flows near the dune brink suggests differences in the aeolian environment possibly due to wind speed and direction unconducive to smaller grainflow formation further down the slipface slope.

The two freshest hourglass grainflows on the central portion of the dune were also thinner than the Maspalomas hourglass grainflows and redistributed significantly less volume of sediment compared to terrestrial hourglass grainflows despite having a greater planform area (Table 1). Terrestrial hourglass grainflows were highly variable in the amount of sediment redistributed for each grainflow due to variability in area (Table 1; Fig. 9) and the Namib dune may also have high variability in grainflow area (Fig. 2, 3, and 4). In addition, when compared to other older grainflows on the Namib slipface, the two measured (and freshest) hourglass grainflows may be smaller than typical Mars grainflows and may have formed in response to slope destabilization from slumping (Fig. 3 and 5). The difference in martian grainflow thickness of lobe, funnel and hourglass grainflows compared to terrestrial grainflows may be
characteristic of all grainflows on Mars. Slopes may be more easily destabilized with less sediment load due to the lower surface gravity and its effect on grain packing. However, more measurements of martian grainflow thicknesses and attributes of grain texture related to angle of repose are required for a more definitive conclusion.

Any grainfall that may have occurred on the Namib dune slipface during the most recent aeolian activity appears to be ineffective at erasing previous grainflow events with the exception of the lee slopes of the barchan horns, where some infilling of alcoves has occurred (Fig. 2 and 4). Under terrestrial conditions, grainfall rapidly erases previous slipface activity and restores the slipface to a critical angle of repose, resulting in a continuous cycle of avalanching and slope restoration (e.g. Bagnold et al., 1941; Allen, 1970; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1995; Nickling et al., 2002; Cupp et al., 2006; Sutton, 2012; Sutton et al., 2013a,b). On the central portion of the Namib dune, there is very little evidence of grainfall or any kind of sediment redistribution following the most recent grainflow activity (Ewing et al., 2017; Fig. 3). Outside of the central portion of the dune slipface, grainfall appears limited to the upper slopes of the slipface (Fig. 2, 4, and 5) and portions of the dune apron, likely as a result of along slope transport from an easterly wind direction, where grainfall was preferentially deposited on west-facing slopes of hourglass grainflow alcoves and small, incipient ripples formed on east-facing slopes (Ewing et al., 2017).

It is likely that sediment delivery to the slipface via grainfall is intermittent or punctuated at certain times of the martian year based on seasonal changes of the wind direction and magnitude (Fig. 7). The absence of smaller grainflows on the mid slope suggest that the grainfall zone for the most recent grainflow event was limited to the uppermost part of
the Namib dune, suggesting low velocity winds (Nield et al., 2017; Cornwall et al., 2018). However, the existence of older, larger hourglass grainflows testifies of greater wind velocities which are required to supply the sediment load necessary to initiate these flows and successfully transport sediment to the base of the lee slope (Nield et al., 2017). It is possible that small grainflows do not form on the mid slope of the Namib slipface in any season if grainfall and saltation lengths are ineffective at causing mid slope over steepening. Alternatively, smaller grainflows may have been overridden by larger flows from a previous, more energetic event and the most recent grainflow activity may be the result of SE winds from the summer season.

3.4.2 Tensional Cracks

Slab flows in the Maspalomas dune field initially manifested as a series of horizontal tensional cracks that ran parallel to the dune brink (Fig. 9 and 10; Table 1; Cornwall et al., 2017). While slab flows have not been extensively studied, there are a number of factors that may influence the formation of these large grainflows on Earth, including the presence of liquid water, ice, or salt (McKee et al., 1971; McKee and Bigarella, 1972; Morris et al., 1972; Bigarella, 1975), complex airflow patterns that affect sediment deposition (McDonald and Anderson, 1995; Nickling et al., 2002; Cupp et al., 2005), or slump degeneration and dry cohesion (Fryberger and Schenk, 1981; Sutton et al., 2013b).

The presence of complex airflow patterns having a significant impact on slab formation, where the most recent seasonal winds are likely from the southeast, seems unlikely. The Namib dune slipface has multiple tensional cracks near the dune crest on the central portion of the
dune and also exhibits a break in slope (Fig. 5a) that is not present elsewhere on the slipface (Fig. 2 and 4). This break in slope may have been a slab flow in progress which was halted possibly due to sediment cohesion from ice or geochemical precipitates or lack of sufficient sediment load to keep the flow moving to the base of the slipface. Induration from ice or geochemical precipitates may be common on martian dunes (e.g. Malin and Edgett, 2001; Bourke, 2004; Bourke, 2005; Fenton et al., 2005; Schatz et al., 2006, Bourke et al., 2008; Gardin et al., 2011). Small amounts of cements such as salt in aeolian deposits can greatly affect threshold shear velocity (Nickling and Ecclestone, 1981) and therefore also impede the initiation and subsequent mobility of grainflows, causing the cessation of slipface advancement during autumn and winter. However, an extremely low volatile content was measured at the Namib dune during late autumn (e.g. Ehlmann et al., 2017) and the only crystalline sulfate mineral present was anhydrite at less than 1.5 weight percent (Achilles et al., 2017). Therefore, it seems more likely that the slump feature may have halted due to lack of momentum.

3.4.3 Stoss Migration and Grainflow Initiation

An alternative mechanism to grainflow initiation from lee slope oversteepening due to grainfall may occur on the Namib dune at certain periods throughout the martian year and may influence the formation of larger hourglass grainflows. The Bagnold dunes are actively migrating at an estimated rate of 0.75 m per Mars year (Silvestro et al., 2013). Superimposed on top of these dunes are large ripples, having a height of 10 cm and spacing between 1 to 2 m (Lapotre et al., 2016; Ewing et al., 2017). These ripple height estimates are likely a lower boundary estimate because measurements were performed at the base of
Figure 11. Namib dune as seen from HiRISE satellite image ESP_018920_1755 (top) and the large stoss ripples as seen from Curiosity (bottom). Red dot indicates the location of the Curiosity rover when the bottom image was taken by the mastcam on sol 1192 of the mission. The large ripples are actively migrating on the stoss slope and obliquely intersect the dune crest line, potentially introducing significant amounts of sediment on to the slipface thus triggering large grainflows.
the secondary lee slope of the Namib dune (Lapotre et al., 2016; Ewing et al., 2017), where ripple wavelengths and heights are generally smaller compared to ripples on the stoss slope. The large stoss ripples migrate at a faster rate of approximately 1.27 m per Mars year as measured from a similar barchan dune southwest of Namib dune (Silvestro et al., 2013). The large stoss ripples intersect the Namib dune crest obliquely (Fig. 11) along the slopes of the barchan horns and transversely along the central slipface (Ewing et al., 2017), resulting in an undulating morphology at the dune brink (Fig. 2, 3, 4, and 5). The occurrence of hourglass grainflow events on the Namib dune may be augmented by the migration of these large stoss ripples, especially during times of the martian year when winds have a more easterly or westerly component (Fig. 7). As the stoss ripples intersect the dune brink, sediment spills on to the upper slopes of the slipface, creating localized over steepening without grainfall, similar to the migration of terrestrial dunes on draas (Ewing et al., 2017). This would result in periodic grainflows along the slipface slopes during seasons of otherwise inactivity but may not be substantial enough to foster significant slipface advancement.

It is possible that this mechanism of grainflow initiation via ripple migration was active during the summer season when the southeasterly winds were more active. High magnitude northerly winds have the potential to produce grainfall and grain saltation over the entire dune slipface. Without northerly winds to transport sediment on to the slipface, there would be very little grainfall to restore the slipface for subsequent grainflow activity, especially along the central portion of the slipface. Therefore, if ripple migration does influence grainflow activity, the process would eventually terminate, leaving behind a few fresh grainflows and very little evidence of grainfall, or slope restoration. This might explain how the Namib dune continues to
advance during the summer season, as evidenced by HiRISE monitoring (Bridges et al., 2017), despite wind conditions being contrary to dune orientation and unconducive to grainfall. The older hourglass grainflows mantled in impact ripples may be the product of this process which is likely ongoing throughout the summer. Once formed, the grainflows would be subject to sediment redistribution from the SE winds, creating impact ripples across the slope but these winds would ultimately be ineffective at restoring the slipface compared to northerly winds that generate extensive grainfall. In addition, sediment deposition on to the slipface from ripple migration might also explain why Curiosity images from late autumn showed little evidence of grainfall deposits and smaller grainflows that preferentially formed just below the brink (Fig. 2, 3, 4, and 5).

### 3.4.4 Seasonal Activity

With little evidence of grainfall on the Namib slipface, it is likely that slipface activity occurs in stages throughout the martian year, similar to the seasonal migration observed at the Nili Patera dune field (Ayoub et al., 2014) or the seasonal erosion and rebuilding observed in polar dunes on Mars (Hansen et al., 2011). Local wind magnitude and direction changes drastically throughout the martian year (Fig. 7) and grainflow activity and slope rebuilding may be controlled by these seasonal changes (e.g. Newman et al., 2017; Bridges et al., 2017).

There may be a season of prolonged ripple migration, where winds have a more eastern or western component, such as the summer. Under these conditions, sediment may be regularly introduced on to the slipface via large stoss ripples that intersect the dune brink obliquely and grainfall may be confined to the lee slope of the horns (Ewing et al., 2017). Lobe
and funnel flows most likely preferentially form just below the dune brink due to the seasonal wind direction, which is incapable of transporting sufficient sediment for over steepening on the mid slope region. Winds incident or oblique to the slipface may be conducive to ripple migration and lateral sediment transport but may not be sufficient for rebuilding the slipface slope for subsequent grainflow, where additional sediment input may be required to achieve a critical angle of repose. It is possible that during periods when the wind directions are more easterly or westerly, grainflow recurrence becomes more punctuated and may cease completely until northern winds resume and restore the slipface.

During northerly wind events, there may be more widespread rainfall and regular grainflow activity, including lobe and funnel flow initiation mid slope as opposed to just below the dune brink. Slope restoration may also be enhanced by complex airflow patterns, such as airflow diversion around the barchan dune resulting in lateral transport to the east (e.g. Ewing et al., 2017), capable of further redistribution of sediment across the slipface. Future investigations involving seasonal airflow modelling may be able to resolve some of these seasonal wind patterns that potentially play a crucial role in slope restoration and grainflow initiation at the Namib dune and other dunes on Mars.

3.4.5 Implications for the Martian Rock Record

Due to the thin nature of the grainflows preserved on the Namib dune, the recognition or preservation of grainflows in the martian rock record may be difficult. The Stimson formation is composed of cross-bedded sandstones and located near the base of Aeolis Mons (Mount Sharp) and has been determined to be a record of a dry-aeolian dune system (Banham et al.,
While many aeolian structures have been identified such as wind ripple stratifications and compound dune bedforms, within cross-sets, there has been no conclusive evidence of grainflow strata (Banham et al., 2018). The absence of grainflow structures in the Stimson formation may be due to reworking of the lee slope by migrating ripples which appear to occur regularly on the Namib dune (Eastwood et al., 2012; Lapotre et al., 2016; Ewing et al., 2017; Banham et al., 2018). If the thinness of grainflow deposits on the Namib dune is typical of martian aeolian environments, grainflows may be rapidly erased or reworked before preservation can take place.

Alternatively, the lack of grainflow strata may not be representative of all martian aeolianites and may be heavily influenced by changes in the planet’s obliquity. Wind directions are little affected by orbital changes while wind speeds can vary significantly and may have a great impact on aeolian activity (Fenton and Richards, 2001). Aeolianites that contain grainflow strata could be representative of dunes that formed under high obliquity when winds speeds are greater and aeolian activity more consistent. Under these conditions, grainflows would be quickly buried by rainfall and preserved as opposed to being reworked by wind ripples. In addition, greater wind speeds would result in a higher sediment flux, increasing grainflow frequency and potentially the grainflow thickness, thereby increasing the probability of preservation in the rock record. During periods of greater obliquity, seasonal variations in slipface activity may also be preserved. For example, early spring is more conducive to grainflow activity and slipface advancement for the Namib dune, while the southeast summer winds promote ripple formation and migration on the stoss and lee slopes (Bridges et al., 2017;
Ewing et al., 2017). Under a more active aeolian environment, these seasonal cycles may be well preserved in the martian rock record.

3.5. Conclusion

The aeolian structures preserved on the Namib dune on Mars are very similar to terrestrial slipface features. However, the level of preservation for each grainflow, ripple, and tensional crack on the Namib dune suggests that rainfall contributed very little to slipface reworking at the time the Curiosity rover visited the dune. Based on terrestrial observation, sediment input from the stoss slope is essential for the formation of larger grainflows, such as hourglass flows, because they are typically initiated by localized slope oversteepening just below the dune brink from saltating sediment delivered from the stoss slope (e.g. Allen, 1968; Allen, 1979; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1992; 1995; Nickling et al., 2002; Kok et al., 2012; Sutton et al., 2013a,b). Therefore, evidence of deposition from saltation or suspension settling is expected with the presence of hourglass grainflows but is limited to the lee slopes of the horns on the Namib dune slipface. In addition, the formation of small lobe and funnel grainflows just below the dune brink also suggests a wind environment incapable of sediment delivery further downslope.

The Curiosity rover visited the Namib dune late autumn, during a time of low aeolian activity (Bridges et al., 2017). Prior to the autumn season, winds were predominantly from the southeast, obliquely incident to the dune slipface. These winds would be ineffective at generating rainfall across the entire Namib dune slipface but conducive to stoss ripple migration. An additional source of sediment, potentially triggering grainflow activity under winds contrary to dune orientation, may be from the sediment deposited from large stoss
ripples on the Namib dune that intersect the dune brink obliquely during migration. The advancement of these large ripples would regularly deposit sediment on to the slipface and the most recent slipface activity may have been generated under this mechanism of sediment transport which would explain slipface advancement throughout the summer season as seen from HiRISE-based monitoring (Bridges et al., 2017) and the existence of a series of hourglass grainflows with little indication of rainfall deposition as well as lobe funnel flows confined to just below the dune brink.

This study has significant implications for understanding modern aeolian dynamics including mechanisms for slipface advancement, dune migration rates, and interpretations of sedimentary structures on Earth, Mars, and other bodies with aeolian deposits. The presence or absence of grainflow strata in martian aeolianites potentially suggests times of high and low obliquity. Changes in obliquity have a substantial impact on aeolian processes (Fenton and Richardson, 2001), potentially affecting the types of aeolian structures that are preserved in the rock record. The study of recent grainflows and other aeolian structures directly impact our understanding of aeolianites such as those found at Meridiani Planum (Grotzinger et al., 2005) as well as the aeolian cross-beds of Aeolis Mons (Banham et al., 2018) and may provide valuable insights into the paleoenvironments in which they formed.

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CHAPTER 4

Seasonal Variations in Airflow Over the Namib Dune, Gale Crater, Mars: Implications for Dune Dynamics

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Abstract

Microscale airflow modelling provides new insights on aeolian bedform response and complex near surface wind patterns not previously resolved by mesoscale models. At a 1-m surface resolution, Curiosity wind data is used to investigate the aeolian environment of the Namib dune on Mars, providing improved seasonal constraints on grainfall, grainflow activity and ripple migration. Based on satellite images, airflow patterns, and surface shear stress, enhanced aeolian activity and slipface advancement occurs during early springtime. Autumn and winter winds are also favorable to aeolian activity but minimal movement was detected in satellite images overlapping with wind data, suggesting that some mechanism inhibited grainflow. During the summer, the migration of large stoss ripples on the Namib dune may augment sediment deposition on the slipface. These results provide a better understanding of the overall migration pattern of the Namib dune which can be extrapolated to other dunes in the Bagnold Dune Field.

4.1 Introduction

The Namib dune located in the Bagnold Dune Field in Gale Crater was one of the first dunes to be visited by a Rover, providing the first in situ observations and sediment analysis of martian dunes. Images taken by the Curiosity rover in 2014 revealed a detailed record of multiple grainflows, ripple formation, and tensional cracks (Ewing et al., 2017; Cornwall et al., 2018a) on the slipface of the Namib dune. The features are similar to terrestrial dunes, having a series of hourglass-shaped grainflows and a small number of lobe and funnel flows (Fig. 1; Cornwall et al., 2018a).
Figure 1. Image showing the similarities between terrestrial (left) and martian (right) grainflow morphologies. Different morphologies are mapped in different colours to accentuate similarities. Hourglass grainflows are mapped in red (A, D and E), smaller grainflows (lobe and funnel morphologies) are mapped in magenta (B, D, and E), slab flows are mapped in orange (D). Tensional cracks and folds commonly associated with slab flows on Earth are also mapped in yellow (C and D), where image insets C and D show the progression of a slab flow on Earth. It is unclear if the tensional cracks mapped on the Namib dune on Mars (E) are related to a slab flow. Ripples have also been mapped in blue on the Namib dune slipface (E) but are absent on the terrestrial dune slipface. Grainflow terminology is taken from a study conducted by Cornwall et al. (2018).
The Bagnold dune field is active (Silvestro et al., 2013) but the Curiosity rover visited Namib dune during late southern autumn, a time of apparent decreased aeolian activity and no significant sediment movement was detected (Bridges et al., 2017). The martian atmospheric density and gravity are much lower than on Earth and this has a significant impact on aeolian processes, where wind speeds must be 7x greater to initiate grain saltation. However, once a grain is in motion, it can more easily stay mobilised at a lower shear stress through energy transfer during grain impacts (Greeley et al., 1980; Greeley and Iversen, 1985; Kok and Renno, 2009; Kok, 2010a,b; Kok et al., 2012). Despite the lack of observed activity, the preserved grainflows on the slipface indicate that the Namib dune does experience aeolian conditions favourable to rainfall and grainflow. However, it is unclear precisely when this activity occurred and whether the grainflows occurred shortly before Curiosity’s visit to the dune or earlier in the martian year.

Much of the airflow modelling research on Mars has focused on global scale patterns with General Circulation Models (GCMs) which have provided a valuable foundation for understanding atmospheric-surface interactions (e.g. Leovy and Mintz, 1969; Greeley et al., 1993; Haberle et al., 1993; Hourdin et al., 1995; Lee and Thomas, 1995; Fenton and Richardson, 2001; Richardson et al., 2002). However, inspection of a few aeolian dune orientations on Mars indicated wind directions contrary to GCM outputs, especially dunes located within craters, suggesting more localized wind patterns may be influencing the dune morphology, (e.g. Greeley et al., 1993; Fenton et al., 2005; Greeley et al., 2006; Hayward et al., 2007; Hayward et al., 2008; Hayward et al., 2009). An understanding of aeolian morphodynamics on Mars requires a spatial scale significantly less than the dimensions of a dune to properly assess how local wind
patterns affect dune morphology. Mesoscale climate models have reduced this resolution gap considerably but are better suited for dune field airflow analysis as opposed to individual dunes, having a resolution of about 500 m (e.g. Rafkin et al., 2001; Toigo and Richardson, 2002; Tyler et al., 2002; Fenton et al., 2005; Richardson et al., 2007; Spiga and Forget, 2009; Hobbs et al., 2010; Pla-Garcia et al., 2016; Rafkin et al., 2016; Newman et al., 2017). An advantage to mesoscale modelling is that it provides a regional context of short-timescale wind flow variability due to complex interactions between the atmosphere and the surface which are important for more localized modifications in dune fields and their long-term migration patterns.

Mesoscale climate modelling, wind and bedform morphology analysis as well as sand grain motion have been studied for the Bagnold Dune Field and a bimodal wind regime, influenced by the crater floor topography, has been identified with primary winds from the NW and secondary winds from the NE (Hobbs et al., 2010; Silvestro et al., 2013; Day and Kocurek, 2016; Silvestro et al., 2016; Newman et al., 2017; Bridges et al., 2017). These mesoscale models for the Bagnold Dune field were conducted at a horizontal resolution of hundreds of meters, and details of individual dunes and near surface wind patterns could not be resolved (Pla-Garcia et al., 2016; Rafkin et al., 2016; Newman et al., 2017). At these mesoscale circulation model resolutions, forcing mechanisms that drive dune migration cannot be studied in full detail, preventing a more comprehensive understanding of aeolian processes that may be in operation. Therefore, a finer resolution airflow model is warranted to effectively study bedform response to the local wind forcing. Recent efforts have employed 3D microscale computational
fluid dynamics modelling with a resolution <5 m to investigate these smaller airflow patterns and how they influence dune morphology and sediment transport (Jackson et al., 2015).

To gain a better understanding of the airflow patterns responsible for aeolian processes on the Namib dune, Mars, a microscale model is employed using a High Resolution Imaging Science Experiment (HiRISE) Digital Terrain Model (DTM) of the dune at a 1-meter horizontal resolution. At this resolution, sub-dune scale bedforms are resolved, providing a more comprehensive investigation of the complex airflow patterns affecting dune morphology (Jackson et al., 2015). The local topography can significantly influence wind speed and direction, thereby also affecting surface shear stress and potentially enabling sediment transport or redistribution during seasons of low magnitude winds. Constraining times of grainflow activity and ripple migration is crucial to understanding aeolian dynamics on Mars. Ripple migration throughout the martian year, especially under varying wind directions may also have a significant impact on sediment transport (e.g., during dust storms). The large ripples migrating on the stoss slopes of the dunes in the Bagnold dune field appear to intersect the dune brinks obliquely and they may be responsible for delivering large volumes of sediment to the slipface (Ewing et al., 2017).

We present a detailed analysis of the local wind regime at the Namib dune, illustrating how and when sediment is redistributed throughout the martian year. Seasonal results of microscale airflow modelling of the Namib dune at an unprecedented resolution are utilised to investigate complex, turbulent and steered airflow that is produced on the lee side and in the immediate vicinity of the Namib dune located in the Bagnold Dune Field (Fig. 2). We illustrate how these complex seasonal flow patterns may affect grainflow activity on the slipface and we
constrain times of aeolian activity throughout the martian year using wind data collected by the Curiosity rover.

Figure 2. Top: CTX/HRSC/Viking composite mosaic showing the location of the Namib dune on Mars (black rectangle below the Curiosity landing site oval) in relation to the Bagnold dune field. Bottom: HiRISE image ESP_044172_1755 of the Namib dune and neighbouring High dune with the curiosity rover in front of the Namib dune slipface. Modified from Cornwall et al., 2018.
4.2 Methodology

A combination of Curiosity Rover Environmental Monitoring Station (REMS) data, a HiRISE DEM, and the open source computational fluid dynamics (CFD) model OpenFOAM, was used to simulate the local wind regime around the Namib dune in Bagnold dune field (-4.686°N 222.364°W). Airflow modelling results were obtained at the resolution of the HiRISE DEM, giving a horizontal resolution of one meter, sufficient to resolve the dune form. This high-resolution modelling provides microscale results that illustrate the influence of complex airflow on sand grain movement and overall dune migration not previously resolved by mesoscale models (e.g. Newman et al., 2017; Pla-Garcia et al., 2016; Rafkin et al., 2016).

4.2.1. Mars Science Laboratory Curiosity Data

Curiosity’s traverse to Mt. Sharp intersected the Bagnold Dune Field, giving the opportunity to collect image data of active aeolian deposits. The Mastcam images used in this study were collected during the rover’s visit to the Namib dune slipface and HiRISE satellite images of the study area coincident with the rover’s visit to the Namib dune. The wind data used for airflow modelling conditions were collected by the REMS over one martian year (687 Earth days). The data includes southern summer (Ls 270°) spanning Curiosity mission sols 864 – 1018; autumn (Ls 0°) sols 1019 – 1211; winter (Ls 90°) sols 1212 – 1389; and spring (Ls 180°) sols 1390 – 1485 (Fig. 3 and Fig. 4).
Figure 3. Left: HiRISE image ESP_018920_1755 showing approximate path of the Curiosity rover spanning the start sol and the end sol of the REMS wind data included in the study. Sols of wind data for one martian year were chosen based on proximity to the Namib dune to present a more accurate representation of the local wind regime. Summer sols are indicated by green dots; autumn, orange; winter, blue; and spring, yellow. Excluded sols due to data quality include: 874-879, 913, 938, 955-956, 1070, 1147-1152, 1161, 1165, 1176-1177, 1187-1188, 1193, 1199, 1247, 1260, 1269, 1285, 1293, 1295, 1308, 1313, 1318, 1331, 1389, 1390-1397, and 1417. Right: Elevation map of the left image created from the HiRISE DTM DTEEC_018854_1755_018920_1755. Total change in elevation throughout rover traverse on the left is approximately 152 m. The increasing elevation toward Mt. Sharp may result in a wind ‘speed up’ zone, accelerating wind speed upslope.
The loss of functionality of one of the two wind sensors on the Curiosity rover does introduce some uncertainty in the REMS data, specifically for wind speed and direction. To ensure the most reliable wind data from Curiosity, the REMS data was restricted based on the wind sensor confidence level, which is dependent on rover function and ambient conditions.
For modelling purposes, we excluded observations with weakened data reliability due to ambient air temperatures less than 50°C, electronic noise, rover movement, incorrect wind sensor configuration, and rear wind direction. In addition, wind data used in this study may have been affected by local topography along Curiosity’s traverse toward Mt. Sharp, temporarily manipulating wind direction and potentially wind speed on certain days. Although the remaining wind data may still contain errors, a comparison between predicted wind direction and velocity from the Mars Regional Atmospheric Modelling System and REMS data are in good agreement (Pla-Garcia et al., 2016) and therefore the remaining data, averaged over an entire season, is deemed reliable for microscale modelling.

4.2.2. HiRISE DTM and Surface Mesh Generation

Airflow modelling results were gathered using a HiRISE DTM DTEEC_018854_1755_018920_1755_U01 with a 1 m/pixel resolution. In preparation for modelling, the HiRISE DTM was reformatted into a StereoLithography (STL) file format suitable for Computational Fluid Dynamics (CFD) modelling in OpenFOAM.

The original HiRISE stereo image pairs had a resolution of ~0.25m/pixel. Generating the DTM from the stereo pairs reduced the resolution to one meter, causing significant smoothing of crucial dune topographic features, specifically the dune brink. Preliminary modelling results lacked the expected complex airflow patterns on the lee side of the Namib dune, such as flow detachment (Schatz and Herrmann, 2006; Delgado-Fernandez et al., 2013; Smyth et al., 2011, 2012, 2013), vortices (Jackson et al., 2011, 2013), and eddies (Wiggs and Weaver, 2012) that are common occurrences on terrestrial dunes. The absence of flow separation from the dune brink
was caused by this smoothing, where instead of a sharp dune brink as seen in Curiosity’s Mastcam images, the dune brink had been artificially rounded. To correct for this smoothing effect, the points along the brink were restored in the STL file to their approximate locations using 3D printing software, Meshmixer, designed to manipulate triangle meshes of 3D objects. No other aspects of the 3D surface were altered. Using the edited STL surface, another simple airflow model was run and the results were successful in showing flow detachment from the Namib dune brink, including vortices, and eddies on the lee side of the dune.

4.2.3. CFD Modelling

Airflow modelling over the Namib dune used OpenFOAM, an open-source CFD modelling software in conjunction with the HiRISE DTM, detailed above. The Reynolds-averaged Navier-Stokes k-ε model was used in this study to investigate intricate lee slope airflow patterns and employs two extra transport equations to represent turbulent properties of flow. These equations predict turbulent kinetic energy (k; Eq. 1) and the rate of dissipation of that energy (ε; Eq. 2).

\[
k = \frac{u^*}{\sqrt{C_{\mu}}}
\]  
(Eq. 1)

\[
\varepsilon = \frac{u^*}{k(z_0 + z)}
\]  
(Eq. 2)

Where \(u^*\) is the shear velocity, \(C_{\mu}\) is a model constant equal to 0.09, K is the Von Karman’s constant equal to 0.43, \(z_0\) is the aerodynamic roughness length, and \(z\) is the reference height. The basic Atmospheric Boundary Layer conditions assigned at the inlet for this model include
free stream velocity ($U$; Eq. 3), turbulent kinetic energy (Eq. 1), and energy dissipation (Eq. 2; Richards and Norris, 2011).

$$U = \frac{u_s}{k} \ln \left( \frac{z + z_0}{z_0} \right)$$  \hspace{1cm} (Eq. 3)

A surface roughness ($z_0$) value of 0.002 was used during modelling, which is an estimate of surface roughness determined by Hebrard et al. (2012) from Mars Global Surveyor Thermal Emission Spectrometer rock abundance data for the study area.

Airflow results were obtained by conducting model runs using 5-meter cells of the topographic meshed surface up wind of the Namib dune. We use simple grading in the z-direction to refine airflow turbulence closer to the surface as well as a refinement region, containing the Namib dune, which further refines the surface to 1-meter cells equal to the HiRISE DTM resolution. Additionally, to capture the enhanced brink line, an additional utility within OpenFOAM was used that extracts feature edges from the geometry surface and then explicitly specifies the features during meshing where points on the mesh boundary are attracted to the nearest points of the supplied feature edge. In this way, the airflow model successfully captures the detached flow from the Namib dune brink in a more realistic manner.

Multiple iterations were run for each martian season, adjusting wind speed and direction as well as atmospheric conditions (Table 1). Average wind speeds and directions for each season were calculated using the most reliable Curiosity REMS data (Fig. 5). Martian atmospheric dynamic viscosity for CO$_2$ was calculated from Sutherland’s formula (Crane Company, 1988) and subsequently converted to kinematic viscosity (per model requirements) by dividing dynamic viscosity by 0.02 kg m$^{-3}$ which is the atmospheric density of Mars (Hecht, 2002). Dynamic viscosity varies according to temperature and using the temperatures recorded
by Curiosity REMS data, we calculate that kinematic viscosity ranged from 6.00e-4 to 6.34e-4 m² s⁻¹ during times of observation between sols 864 -1485.

Table 1. CFD model input parameters, including seasonal average REMS wind direction (degrees azimuth), speed and ambient temperature with the calculated atmospheric kinematic viscosity. REMS Wind conditions for each season include primary, secondary and tertiary wind characteristics, where present and correspond to wind data plotted in figures 4 and 5. Model output is the surface shear stress, where the maximum values are shown here and correspond to values shown for each season in figures 6-12.

<table>
<thead>
<tr>
<th>Season</th>
<th>REMS Wind Direction (Degrees)</th>
<th>REMS Wind Speed (m/s)</th>
<th>REMS Ambient Temperature (K)</th>
<th>Kinematic Viscosity (m²/s)</th>
<th>Max Surface Shear Stress (kg/ms²)</th>
</tr>
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<tr>
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<td>(sols 864 - 1018)</td>
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<td>8.25</td>
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</tr>
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<td></td>
<td></td>
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<tr>
<td>(sols 1390 - 1485)</td>
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<td>Primary</td>
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<td>249.84</td>
<td>6.34E-04</td>
<td>0.027</td>
</tr>
<tr>
<td>Secondary</td>
<td>142.51</td>
<td>7.70</td>
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<td></td>
<td>0.015</td>
</tr>
</tbody>
</table>
Figure 5. Rose diagrams showing seasonal wind trends from REMS wind data. Springtime winds are primarily from the north with secondary, reduced wind speeds from the south. Summer winds are weaker and originate from the southeast. Primary autumn winds are from the northeast with secondary winds from the west northwest and tertiary weak winds from the southeast. Lastly, winter winds are primarily from the northwest. Some scatter in the data may be due to local topographic effects but the general trends agree well with mesoscale models of Gale Crater. CFD modelling results are based on these general seasonal trends as input to the model.
4.3 Results

The local wind regime in Gale Crater is complex, with a wide range of wind directions and magnitudes during a single Mars year (MY), including MY32 summer and of MY 33 autumn, winter and spring. REMS data indicates that the near surface winds predominantly originated from the north and were the greatest in magnitude (Fig. 4). This agrees with dune orientation and overall patterns of dune migration to the south. Lesser magnitude winds also occurred and it appears that southerly winds may also have had an impact on dune morphology and slipface processes. Here we present modelling results for each martian season in relation to wind direction and velocity.

4.3.1. Seasonal Patterns

4.3.1.1. Spring (Ls 180°)

The higher magnitude winds in the springtime occurred early in the season, largely between ~sols 1400 – 1430 and originated from the north (Fig. 5) with an average wind velocity of 9.84 m s⁻¹ (Table 1). The more predominant but lesser magnitude winds during the spring varied between east, southeast, and southwest (Fig. 5). These secondary winds had an average wind speed of 7.70 ms⁻¹ (Table 1).

Modelling the higher magnitude northerly winds during spring generated significant turbulent flow on the lee side of the Namib dune, where detached flow from the dune brink and complex helical flow was observed (Fig. 6a). There was also a component of lateral airflow to the east from the helices along the slipface (Fig. 6c and d). High amounts of surface shear stress were present in most areas of the stoss slope and greatest along the dune brink with a
maximum value of $0.027 \text{ kg m}^{-1} \text{s}^{-2}$ (Fig. 6b) with near surface winds reaching approximately 17 m s$^{-1}$ (Fig. 6c and d).

The more frequent southerly winds during spring, as modelled from the southeast, did not display any complex airflow patterns (Fig. 7a). Southerly winds flowed up the Namib slipface and over the brink, closely following the topography (Fig. 7c and d) and generated elevated surface shear stress values, concentrated along the dune brink, having a maximum
value of about 0.015 kg m$^{-1}$ s$^{-2}$ (Fig. 7b). The maximum near surface wind velocities were approximately 13 m s$^{-1}$ (Fig. 7c and d).

Figure 7. (A) Velocity streamlines of spring secondary winds from the southeast showing flow detachment and vortices on the lee side of the Namib dune (-4.686°N 22.364°W), (B) surface shear stress including the viewer locations on the surface for panels C and D, and wind flow vectors as viewed from (C) the west flank of Namib dune and (D) the opposite east flank of the dune, where the surface of panels C and D represent surface flow speed.
4.3.1.2. Summer (L, 270°)

Wind direction during the summer was generally from the southeast but also ranged between NE to SSW (Fig. 5). There was no secondary wind direction identified and modelling results display southeast winds only. Average REMS wind velocity was approximately 6.46 m s\(^{-1}\) (Table 1) and modelling results showed no indication of complex airflow (Fig. 8a, c, and d),
similar to the southeast winds during spring. The maximum surface winds reached approximately 11 m s\(^{-1}\), lower than spring winds originating from the same direction. With the lower surface wind velocities during the summer season, there was also a decrease in surface shear stress around the Namib dune (Fig. 8b). The more pronounced areas of surface shear stress occurred along the dune brink, reaching a maximum of approximately 0.009 kg m\(^{-1}\) s\(^{-2}\).

4.3.1.3. Autumn (\(L_0^o\))

Autumn winds originated in three distinct directions during MY 33. The greatest magnitude winds (primary winds) were from the northeast, followed by secondary winds from the northwest and the lesser-magnitude tertiary winds from the southeast (Fig. 5). Winds fluctuated in all directions throughout the season but the general shift in wind direction was toward the north near the end of the season.

The average REMS wind speed of the primary wind direction from the northeast is about 8.25 m s\(^{-1}\) (Table 1) and generated complex airflow on the lee side of the Namib dune (Fig. 9a). Compared to the spring northerly winds, the autumn northerly winds had a more eastern component and there was less lateral flow to the east from helices along the slipface (Fig. 9a, c, and d). There was, however, a more pronounced backflow up the slipface slope when compared to spring (Fig. 9c and d). Greater values of surface shear stress were present on the stoss compared to those generated from the southeast winds of spring and summer. The greatest amounts of surface shear stress were along the dune brink, reaching 0.022 kg m\(^{-1}\) s\(^{-2}\) (Fig. 9b) with near surface wind velocities reaching 15 m s\(^{-1}\).
The secondary autumn REMS wind speeds averaged about 6.74 m s\(^{-1}\) (Table 1) and originated from the northwest. These winds did not produce any complex airflow (Fig. 10a) and simply followed the dune topography (Fig. 10c and d), similar to southeast winds. Near surface modeled wind speeds reached 12 m s\(^{-1}\) and surface shear stress had the greatest affect along the western flank of Namib dune (Fig. 10b) with a maximum value of about 0.013 kg m\(^{-1}\) s\(^{-2}\).
The tertiary southeastern autumn winds had the lowest average REMS wind speed of 5.05 m s\(^{-1}\) (Table 1) and generated no complex airflow (Fig. 11a, c, and d). Modeled near surface winds reached a maximum of about 8 m s\(^{-1}\) and were concentrated along the Namib dune brink, generating values of surface shear stress of about 0.006 kg m\(^{-1}\) s\(^{-2}\) (Fig. 11b).

Figure 10. (A) Velocity streamlines of secondary autumn winds from the northwest showing flow detachment and vortices on the lee side of the Namib dune (-4.686°N 222.364°W), (B) surface shear stress including the viewer locations on the surface for panels C and D, and wind flow vectors as viewed from (C) the west flank of Namib dune and (D) the opposite east flank of the dune, where the surface of panels C and D represent surface flow speed.
4.3.1.4. Winter ($L_90^\circ$)

Seasonal wind patterns during winter predominantly originated from the northwest. Winds from the southwest and southeast were not nearly as common in MY 33 and therefore modelling was only conducted for northwest winds which have the most influence on the aeolian environment. The average REMS wind speed for the northwest winds was 8.06 m s$^{-1}$. 

Figure 11. (A) Velocity streamlines of tertiary autumn winds from the southeast showing flow detachment and vortices on the lee side of the Namib dune (-4.686°N 22.364°W), (B) surface shear stress including the viewer locations on the surface for panels C and D, and wind flow vectors as viewed from (C) the west flank of Namib dune and (D) the opposite east flank of the dune, where the surface of panels C and D represent surface flow speed.
Modelling revealed complex airflow on the lee side of the dune (Fig. 12a, c, and d) and included some flow steering around the dune with lateral flow to the east (Fig. 12a). Maximum near surface winds predicted by the model are approximately 15 m s\(^{-1}\) with a maximum surface shear stress value of about 0.023 kg m\(^{-1}\) s\(^{-2}\) along the dune brink (Fig. 12b).

Figure 12. (A) Velocity streamlines of winter winds from the northeast showing flow detachment and vortices on the lee side of the Namib dune (-4.686°N 22.364°W), (B) surface shear stress including the viewer locations on the surface for panels C and D, and wind flow vectors as viewed from (C) the west flank of Namib dune and (D) the opposite east flank of the dune, where the surface of panels C and D represent surface flow speed.
4.4 Discussion

With the results of microscale CFD modelling, the local wind regime around the Namib dune can be examined in detail and better constraints on when sediment is mobilised, when grainflow activity occurs and when the slipface is being reworked can be established. These seasonal modelling results provide a better understanding of the overall migration pattern of the Namib dune which can be extrapolated to other dunes in the Bagnold Dune Field.

4.4.1 Potential Seasonal Sediment Transport.

Threshold constraints for grain movement on Mars are still under debate but there have been a couple of studies that have provided general estimates of effective shear stress and the minimum wind velocity needed to initiate grain saltation on Mars. At Nili Patera, the effective shear stress for grain movement was estimated to be $0.01 \pm 0.0015$ kg m$^{-1}$ s$^{-2}$ (Ayoub et al., 2014). Bridges et al. (2017) estimated that saltation may be initiated for wind speeds greater than 8 to 10 m s$^{-1}$ based on Curiosity rover observations that identified intra-sol changes when the mean wind speeds exceeded 8.5 m s$^{-1}$. The threshold for effective shear stress is used to interpret results here since wind speeds are a product of complex flow and may vary depending on the influence of nearby topography.

4.4.1.1 Potential Spring Sediment Movement

The most influential spring winds in MY 33, based on surface shear stress values, are the primary winds, where the maximum surface shear stress is $0.027$ kg m$^{-1}$ s$^{-2}$ (Fig. 6b). Primary winds in the spring originated from the north and occurred predominantly early in the season.
and were well over the shear stress threshold (0.01 kg m\(^{-1}\) s\(^{-2}\); Ayoub et al., 2014). These winds were likely capable of initiating grain saltation across the stoss slope (Fig. 6b) and there is also evidence of flow detachment at the dune crest and complex helices on the lee side of the dune (Fig 6a, c, and d) which may be accompanied by rainfall. It is likely that early spring is a time of enhanced aeolian activity. The secondary spring winds from the southeast may also initiate grain movement, focused along the Namib dune brink, with maximum surface shear stress values reaching just above the threshold at 0.015 kg m\(^{-1}\) s\(^{-2}\) (Fig. 7b). However, apart from a few isolated areas along the dune brink, sediment may be largely immobile under these wind conditions.

4.4.1.2 Potential Summer Sediment Movement

Average winds during MY 32 summer were primarily from the southeast and weaker than the southeast winds experienced in the following MY 33 spring. Maximum surface shear was just below the threshold value for grain movement at 0.009 kg m\(^{-1}\) s\(^{-2}\) (Fig. 8b) but within the error range of the (± 0.0015 kg m\(^{-1}\) s\(^{-2}\); Ayoub et al., 2014), suggesting that some grain movement may have taken place but it likely did not result in substantial sediment transport or redistribution. Alternatively, since the modelling results are an average of the entire summer season, it is likely that there was periodic grain movement from gusts of wind or higher magnitude winds on certain days. Overall, it appears that summer may be a season of quiescence for aeolian activity.
4.4.1.3 Potential Autumn Sediment Movement

The greatest wind speeds in MY 33 autumn originated from the north. These primary winds, while not as strong as the spring northerly winds, had the potential to initiate sediment saltation across the stoss slope and along the dune brink, where the maximum surface shear stress values reached 0.022 kg m\(^{-1}\) s\(^{-2}\) (Fig. 9b). In addition, flow separation occurred in the modelling results (Fig. 9a) and may have been accompanied by rainfall and potentially grainflow activity. Secondary winds during autumn had a more westerly component but these winds also had the potential for sediment movement, especially along the dune brink with surface shear stress reaching 0.013 kg m\(^{-1}\) s\(^{-2}\) (Fig. 10b). Sediment transport or redistribution was also likely along the western flank of the Namib dune and parts of the western stoss slope (Fig. 10b). Autumn tertiary winds were the weakest and originated from the southeast. These weak winds likely did not initiate any grain movement. Elevated shear stress values were concentrated along the dune brink but, at a maximum value of 0.006 kg m\(^{-1}\) s\(^{-2}\), did not exceed the threshold value for sediment movement (Fig. 11b).

4.4.1.4 Potential Winter Sediment Movement

Winter winds in MY 33 originated primarily from the northwest and generated surface shear stress values sufficient for sediment saltation. The maximum shear stress reached 0.023 kg m\(^{-1}\) s\(^{-2}\), where elevated shear stress values were concentrated along the brink but a large area of the stoss slope also experienced surface shear stress values above the threshold value for grain transport (Fig. 12b). Similar to autumn primary wind patterns, winter airflow patterns also showed flow detachment at the dune brink and complex helical patterns on the lee side of
the dune (Fig. 12 a, c, b) which may have produced some grainfall. Based on modelling results, the winter season on Mars should be conducive to slipface advancement as well as rainfall and grainflow activity.

4.4.2 Implications for Slipface Activity

Slipface activity such as that preserved on the Namib slipface (Fig. 1e) requires large amounts of sediment flux to induce localised slope over steepening near the top of the lee slope, thereby triggering a grainflow. It is through rainfall and a series of grainflows that slipface advancement is achieved (e.g. Bagnold, 1941; Allen, 1970; Hunter, 1977; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1995; Kok et al., 2012). The Namib slipface suggests that at some point(s) during the MY 33, the slipface was very active. However, no grain movement or grainflow activity was observed during the time the Curiosity rover was in front of Namib dune slipface (late autumn), where winds speeds varied between 4 – 7 m s\(^{-1}\) and were strongest from the west (Bridges et al., 2017).

4.4.2.1 Northerly Winds

The magnitude and direction of winds during the Namib dune observation is characteristic of autumn secondary winds (Table 1 and Fig. 10). The greater magnitude winds measured by REMs during this time (> 5 m s\(^{-1}\)) generate surface shear stress values along the western dune flank and brink line up to 0.013 kg m\(^{-1}\) s\(^{-2}\) (Fig. 10b), sufficient for grain transport (Ayoub et al., 2014). Under westerly winds, large portions of the dune slipface are sheltered (Fig. 10a and b) and it is probable that from the perspective of the rover in front of the Namib
dune, no activity could have been observed. Alternatively, the days allocated for grain movement observation by the rover could have been more quiescent than other autumn days and no grain movement occurred across the entire dune. It is therefore unclear how recent the grainflows on the slipface are since the northerly winds, which are more conducive to slipface activity, were not active during rover observation.

Based on CDF modelling results, there are a few times during the martian season, that may be more favourable to grainfall and slipface activity. Some of the seasonal wind patterns may also explain ripple formation around and on the slipface of the Namib dune as well as the maintenance of the ladderback ripple patterns on the stoss slope (Ewing et al., 2017). Northerly winds striking the dune brink between angles 40° to 90° are likely to generate grainfall, airflow separation and complex three-dimensional vortices on the lee side of the dune (Ewing et al., 2010; Eastwood et al., 2012; Ewing et al., 2017), which is consistent with modelling results. Flow separation and the formation of three-dimensional helices occurred during early spring, throughout autumn as well as the winter season (Fig. 6a, 9a, and 12a). Despite the lack of significant grain movement during Curiosity’s visit, it is possible that the imaged slipface activity (Fig. 1e) occurred earlier in the autumn season. It has also been suggested that because Curiosity’s visit to the dunes coincided with some of the colder temperatures of the year, the dune sediment may have been indurated from seasonal frost (Bridges et al., 2017). During the nighttime, a few micrometers of frost can condense within porous spaces of the dune sand, potentially cementing the top layer of sand during the day (Martinez et al., 2016). If this process occurs during colder seasonal temperatures, the dune sediment may be immobilised during much of the autumn as well as winter seasons. Spring exhibited the highest magnitude
northerly winds early in the season and it is therefore a likely time of significant slipface activity and overall dune advancement. It is expected that there is also lateral transport to the east due to the formation of the helical wind patterns on the lee side of the dune (Fig. 6) and depending on the incidence angle of the wind on the brink line, the magnitude of this eastward transport would vary. For example, northwest winds generated much stronger lateral airflow along the lee slope (Fig. 12) than more northerly or northeasterly winds (Fig. 6 and 9). This lateral transport was also sometimes augmented by flow steering around the western flank of the Namib dune (Fig. 12a).

4.4.2.2 Southerly Winds

Other mechanisms of redistribution of sediment and reworking of the Namib slipface may also occur during the martian year. Southerly winds, such as secondary springtime winds and, to a lesser extent, summer winds and autumn tertiary winds (Fig. 7, 8, and 11), can erase slipface features and rework the dune brink, potentially rounding the brink line as sediment is pushed down the stoss slope. Autumn tertiary winds may not affect the slipface at all since the maximum surface shear stress only reaches 0.006 kg m$^{-1}$ s$^{-2}$. However, there may be a few days where secondary autumn wind magnitudes are greater than the average (Fig. 5), resulting in elevated values of surface shear stress. The maximum summer surface shear stress is within the error bounds of the shear stress threshold for grain movement and therefore autumn may be a season of some sediment movement. Similar to the autumn tertiary winds, there were times during the summer season where the wind magnitudes increased above the average wind speed (Fig. 5) which would result in elevated values of surface shear stress, capable of sediment
transport. Spring and summer southerly winds may also affect the stoss slope, maintaining the ladderback ripple pattern observed in Curiosity Mastcam images (Ewing et al., 2017). In addition, the seasonal winds with the more easterly component and sufficient wind speed necessary to generate sediment transport may activate the secondary slipface identified by Ewing et al., (2017) along the western flank of the Namib dune. Autumn secondary winds were more westerly (Fig. 10) and had the potential to redistribute sediment and rework the brink line. These westerly winds may also be highly influential in forming the ripples that cover the Namib slipface (Fig. 1; Fig. 10) as well as reworking the western flank and transporting sediment to the East.

4.4.3 Overall Dune Migration Patterns

The Bagnold dunes are migrating each year, at a pace of about 0.2 m/MY with ripples migrating quicker at a rate of about 0.33 m/MY (Silvestro et al., 2013). The Namib dune was specifically examined to detect change using HiRISE images over one year (MY 33) which overlapped with the time of Curiosity’s visit to the dunes. The Namib dune slipface was clearly seen to advance during MY 33 with a displacement of approximately 0.4 m (Bridges et al., 2017). The stoss ripples moved more rapidly and could not be confidently tracked. Overall sediment movement in the dune field show that the most active seasons in MY 33 for migration are during spring to summer. The least active seasons were autumn and winter (Bridges et al., 2017).

Despite the favorable wind direction and magnitude in the autumn and winter seasons, the Namib dune experienced very little activity according to the HiRISE data. This may be due to
frost condensation in between sand grains and subsequent induration of the dune sediment (Martinez et al., 2016; Bridges et al., 2017). Alternatively, sediment movement may have occurred during this time but at a significantly slower rate than the spring and summer seasons and may not have been detected by HiRISE image monitoring. The lack of significant slipface advancement during any other season besides spring and summer in MY 33 suggest that the preserved slipface activity may have been from earlier in the martian year and very little aeolian reworking has taken place outside these seasons based on the level of preservation of the grainflows and ripples on the slipface.

Periods during the martian year when winds are blowing contrary to the slipface (from the south) such as the summer, and these may be times in which the dune brink is smoothed and sediment is transported down the stoss slope. Alternatively, this may also be a time of enhanced stoss ripple migration, which may introduce significant amounts of sediment on to the slipface as the ripples obliquely intersect the brink (Ewing et al., 2017; Cornwall et al., 2018). Under this mechanism of sediment delivery, the Namib dune slipface may continue to advance during periods unconducive to grainfall on the main slipface. Winds favorable to stoss ripple migration but not grainfall occur throughout the spring and summer, when wind directions can vary from east to southeast or southwest (Fig. 5). However, once a grainflow occurs, there needs to be a way to restore the slipface slope before another grainflow can form (e.g. Bagnold, 1941; Allen, 1970; Hunter, 1977; Hunter, 1985; Anderson, 1988; McDonald and Anderson, 1995; Kok et al., 2012; Cornwall et al., 2018). It is likely that grainflows triggered by stoss slope ripple migration occur throughout the summer season but once multiple grainflows have formed, this mechanism for grainflow activity is terminated until northerly winds can
rebuild the slipface slope. The series of seemingly fresh grainflows imaged by Curiosity during late autumn (Bridges et al., 2017), may be a remnant of summer activity due to ripple migration.

4.5 Conclusion

Microscale CFD modelling has provided, for the first time, the necessary means to better understand the interaction between local wind regime and aeolian bedform response and migration. Here, we examine how the local wind regime in Gale Crater interacts with the Namib dune in the Bagnold dune field on Mars. We discuss how and when the observed slipface morphologies and ripples may form or migrate throughout a martian year and what may affect sediment redistribution based on complex airflow patterns, threshold wind speeds, and surface shear stress values sufficient to move sediment. Based on modelling results and HiRISE observations, the spring season is likely the most active season in regards to grainfall and the formation of grainflows on the slipface. This activity may also continue into the summer season and may be augmented by the large stoss ripples, obliquely oriented to the dune brink, which regularly introduce sediment onto the slipface slope as they migrate (Ewing et al., 2017). The lack of detectable movement in HiRISE images of the Namib dune during autumn and winter, despite wind direction and velocity being favorable to slipface activity, suggests that there is some mechanism that is preventing aeolian processes from operating such as seasonal frost (Martinez et al., 2016; Bridges et al., 2017) or the rate of slipface modification is slower than what can be detected by HiRISE images.
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CHAPTER 5

Diurnal Airflow Patterns on Namib Dune, Gale Crater, Mars: Insights from Microscale Modelling

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Abstract

The Curiosity rover has collected near-surface wind data near an active martian dune field which can be used to understand critical details in the local wind environment. Previous attempts at airflow modelling in Gale Crater lacked the necessary resolution to resolve dune forms or small scale local topography that can influence airflow around the dune. Microscale airflow modelling of the Namib dune at a 1 meter resolution is used to investigate how dune morphology and local topography affects near surface wind speed and surface shear stress. We focus on diurnal changes in wind magnitude and direction through a typical summer and winter martian sol and demonstrate how sand-moving winds are likely occurring daily within Gale crater. Computational Fluid Dynamics (CFD) modelling shows a peak in wind speed early to mid-afternoon, corresponding to periods of probable increased sediment transport. Due to these lower magnitude winds, indications of aeolian activity are not as pronounced throughout the summer day, but sediment transport may still occur along the dune brink where surface shear stress is elevated. In contrast, surface shear stress values are elevated throughout much of the winter day, exceeding the values needed to initiate grain movement and saltation.

5.1 Introduction

Aeolian deposits on the surface of Mars are ubiquitous and present at all latitudes, suggesting that windblown processes are the dominant geomorphic agent on the planet today (Sagan et al., 1973; Thomas, 1982). Aeolian airflow dynamics have largely been studied using a combination of general circulation models (Leovy and Mintz, 1969; Greeley et al., 1993; Haberle et al., 1993; Hourdin et al., 1995; Lee and Thomas, 1995; Fenton and Richardson, 2001),
mesoscale models (e.g.; Rafkin et al., 2001; Toigo and Richardson, 2002; Tyler et al., 2002; Fenton et al., 2005; Richardson et al., 2007; Spiga and Forget, 2009; Hobbs et al., 2010; Pla-Garcia et al., 2016; Rafkin et al., 2016; Newman et al., 2017) and continued monitoring through high resolution satellite images (e.g. Bridges et al., 2007; Bourke et al., 2008; Silvestro et al., 2010; Chojnacki et al., 2011; Hansen et al., 2011; Silvestro et al., 2011; Bridges 2011; Bridges et al., 2012). In addition to airflow modelling, wind tunnel experiments and theory for saltation initiation suggested that sand-moving winds on Mars were rare (Pollack et al., 1976; Arvidson et al., 1983; Moore, 1985; Sullivan et al., 2000; Haberle et al., 2003; Chojnacki et al., 2011), contradictory to satellite observations of dune slipface advancements and ripple migration (e.g. Bridges et al., 2007; Bourke et al., 2008; Silvestro et al., 2010; Bridges et al., 2011; Chojnacki et al., 2011; Hansen et al., 2011; Silvestro et al., 2011; Bridges et al., 2012a,b; Bridges et al., 2013; Geissler et al., 2013; Silvestro et al., 2013; Chojnacki et al., 2015; Cardinale et al., 2016; Runyon et al., 2017) with some migration rates comparable to Earth (e.g. Dong et al., 2000; Bristow and Lancaster, 2004; Bourke et al., 2009). While this contradiction may be explained by uncertainties in interparticle cohesion and electrostatics (Newman et al., 2002; Kok and Renno, 2009), the role of localized wind gusts and complex airflow patterns at the dune scale are likely responsible for much of the sediment transport and influences on dune morphology (e.g. Greeley et al., 1993; Fenton et al., 2005; Greeley et al., 2006; Hayward et al., 2007; Hayward et al., 2008; Hayward et al., 2009; Ayoub et al., 2014; Pla-Garcia et al., 2016; Rafkin et al., 2016; Bridges et al., 2017; Ewing et al., 2017; Newman et al., 2017).

Sand-moving winds are now thought to be significantly more common on Mars. A study of the Nili Patera dune field monitoring ripple migration revealed a sustained sand flux
throughout the martian years, suggesting that sand-moving winds may occur daily (Ayoub et al., 2014). Daily sand-moving winds may occur elsewhere on Mars and are likely heavily influenced by local topography that generate turbulent gusts and elevated wind surface shear capable of sediment transport. One such location is in the Bagnold dune field within Gale Crater.

The Mars Science Laboratory (MSL) Curiosity rover captured images of a martian dune at the planet’s surface, providing unprecedented detail of aeolian features such as impact ripples, large ladder-back stoss ripples and grainflows (e.g. Bridges et al., 2017; Ewing et al., 2017). The MSL Curiosity rover is also equipped with meteorological instrumentation and has collected valuable data near and inside the Bagnold dune field in Gale crater providing a unique opportunity to explore the daily airflow patterns within the crater and how these airflow patterns influence dune morphodynamics throughout a single martian day. The Namib dune is part of the Bagnold dune field located on the northern strip of the dune field near the central mound of Gale Crater, known as Aeolis Mons and informally, Mount Sharp (Fig. 1). This area of the Bagnold dune field is sparsely populated by barchan dunes and is influenced by large-scale diurnal airflow patterns controlled by the crater topography. For example, mesoscale modelling in late autumn/early winter season predicts near surface winds that travel up the slopes of Aeolis Mons from the northwest during the day (09:00-17:00) and down the slopes of Aeolis Mons from the southeast at night (~20:00 to just before 08:00; Newman et al., 2017). These mesoscale model predictions agreed well with the general pattern in 1.5 m wind speeds and directions measured by Curiosity Rover Environmental Monitoring Station (REMS) during the Bagnold Dunes Campaign.
Figure 1. (A) Mars Orbiter Laser Altimeter Map of the surface of Mars in elevation with the location of the landing site of Mars Science Laboratory Curiosity rover represented by a circle. (B) CTX/HRSC/Viking composite mosaic showing the location of the Namib dune (-4.686°N 222.364°W) within the Bagnold dune field (C) HiRISE image ESP_018920_1755 of the Namib dune within the Bagnold Dune field with the location of Curiosity at three sols during the mission. Sol 996 data is used in this study to investigate diurnal wind patterns during the summer season, sol 1238 data is used to investigate diurnal wind patterns during the winter season. Sol 1196 is one of many sols in which Curiosity was collecting data and images of the Namib dune sediment and various aeolian morphologies on the stoss and lee slopes (e.g. Fig. 2 and 3).
Near the end of the autumn season, Curiosity spent several Mars days in front of the lee slope of the Namib dune, and REMS data indicated that the daytime winds were from the west instead of the north. These westerly winds were surmised to be the result of airflow diversion around the dune and other nearby topographic obstacles (Newman et al., 2017). In addition, rover wind measurements also indicated an increase in wind variance while situated on the lee side of the Namib dune, which was suggested to be the result of airflow turbulence (Omidyeganeh et al., 2013; Newman et al., 2017). These more detailed airflow structures are unresolved by mesoscale modelling resulting in an under prediction of daytime wind strength as well as the loss of deflected flow patterns from local topography (Pla-Garcia et al., Rafkin et al., 2016; Newman et al., 2017). Complex airflow patterns have a strong impact on aeolian dynamics and are critical in understanding factors that shape dune morphology, sediment transport, and dune migration (Jackson et al., 2011, 2013, 2015; Smyth et al., 2012). To adequately study martian aeolian dynamics, a finer-scale airflow model is required which can resolve individual bedforms and local topography that influence daytime and seasonal airflow.

Using a High Resolution Imaging Science Experiment (HiRISE) Digital Terrain Model (DTM), the microscale CFD model in this study has a resolution of 1 m and is used to investigate how the detailed diurnal wind pattern data, provided by REMS, change in the dune environment. The focus of this detailed airflow modelling is on the Namib dune (Fig. 1). Images of the Namib dune revealed extensive grainflow activity that crosscut previously-formed ripples on the slipface (Fig. 2) as well as complex cross-hatch (ladder-back) ripple formation patterns on the stoss slope (Fig. 3) that suggested influence from multi-directional winds throughout the Mars year (Bridges et al., 2017; Ewing et al., 2017).
A detailed simulation of diurnal wind patterns for the Namib dune gives a unique perspective on the daily aeolian influences on the dune as well as other dunes within the Bagnold Dune field. Two sols of REMS wind data are used to investigate diurnal changes on Mars. The first sol of observation is during the summer season when winds are flowing from the southeast and southwest. This direction is contrary to the Namib dune orientation. The second sol of observation is during the winter season when winds are from the northwest and northeast and align with the dune orientation. Microscale airflow modelling is conducted for every hour of the day with available data to investigate the most likely time of day for sediment transport. Bedform-scale modelling is essential to understand the local wind regime, specifically

Figure 2. Mastcam image of the lee slope of the Namib dune taken by the Curiosity rover (bottom right) at a distance of 15 m from the dune. Lee slope exhibits evidence of slipface activity (grainflows) and vertical ripples crosscut by more recent grainflow. Scale bar is valid for the base of the dune slipface in the centre of the image.
how airflow patterns are altered by topography and how near surface winds can increase surface shear stress, affecting sediment transport even at measured wind speeds below the threshold for grain saltation throughout a Mars day.

Figure 3. Namib dune as seen from HiRISE satellite image ESP_018920_1755 (top) and the large stoss ripples as seen from Curiosity (bottom). Red dot indicates the location of the Curiosity rover when the bottom image was taken by the mastcam (MCAM05410) on sol 1192 of the mission. The large ripples are actively migrating on the stoss slope and obliquely intersect the dune crest line, potentially introducing significant amounts of sediment on to the slipface thus triggering large grainflows.
5.2 Methodology

Airflow modelling of the aeolian environment around the Namib dune (-4.686°N 222.364°W) in Gale Crater is achieved using the open source Computational Fluid Dynamics model OpenFOAM. Airflow modelling results are achieved using a HiRISE DTM with a horizontal resolution of 1 m. This resolution can resolve the dune form and provides microscale results capable of illustrating the influence of complex airflow on daily changes in sand grain movement for each hour of the martian day.

5.2.1 Wind Data

REMS data from mission sols 996 (Ls 348°) and 1238 (Ls 102°) were used for modelling. The primary winds originate from the north and south throughout the martian year (Fig. 4). Sol 996 was chosen to represent a typical southern summer day for Gale Crater where the winds originate from the southeast and are low magnitude (Table 1). Average summertime winds flow opposite to the orientation of the dune morphology (Fig. 4), where winds are incident to the dune slipface. Sol 1238 is a typical day in winter for Gale Crater (Fig. 4) and, in contrast to the summer day, the winds are high magnitude and originate from the north-northwest in agreement with dune morphology (Table 1). These two sols out of the summer and winter seasons were chosen to represent opposite extremes in the aeolian environment as well as the two primary seasonal winds that influence the Namib dune during the year. Summertime winds may result in erosion and significant reworking of dune sediment, redistributing sediment on the slipface and rounding of the dune brink. Wintertime wind orientation and magnitude, which continues into early spring are more conducive to grainflow activity and slipface...
advancement. In addition, these diametrical winds from summer and winter also mimic airflow directionality reversal within the crater, where winds may be northerly during the day and transition to more southerly winds at night (Newman et al., 2016).

Figure 4. Wind rose diagrams from REMS Curiosity data for an entire Mars Year (MY 33), overlapping with the visit to the Namib dune. Summer and winter wind rose diagrams show the dominant wind directions.
Table 1. Hourly averaged REMS wind speed, wind direction and temperature. CFD model input includes the initial REMS wind speed and kinematic viscosity. CFD model output is the maximum surface shear stress, correlating with Figures 7 and 10.

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<th>REMS Wind Direction (°)</th>
<th>REMS Ambient Temperature (K)</th>
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5.2.2 Surface Mesh

The surface generated for use in OpenFOAM airflow modelling was converted from the HiRISE DTM DTEEC_018854_1755_018920_1755_U01 into a StereoLithographic (STL) file and the dune brink-line was enhanced to better represent the true dune morphology. HiRISE DTMs
are generated using stereopairs of HiRISE images that have a resolution of 25cm/pixel. During DTM creation, resolution is reduced to 1 meter/pixel and significant smoothing occurs along the dune brink. This smoothing results in the loss of critical detail needed for accurate airflow modelling. In the absence of a well-defined dune brink, no airflow separation occurs at the crest which affects accurate true representation of airflow patterns on the lee side of the dune. To correct for this smoothing effect, the dune brink was restored in the STL file using Meshmixer. No other aspects of the surface were altered.

### 5.2.3 CFD Modelling

Airflow modelling was accomplished using OpenFOAM software that utilizes the Reynolds-averaged Navier Stokes $k$-$\varepsilon$ model to predict intricate lee slope airflow patterns. This model uses two extra transport equations to represent turbulent properties of flow. These equations predict turbulent kinetic energy ($k$; Eq. 1) and the rate of dissipation of that energy ($\varepsilon$; Eq. 2).

\[
 k = \frac{u_*^2}{\sqrt{C_\mu}} \quad \text{(Eq. 1)}
\]

\[
 \varepsilon = \frac{u_*^3}{K(z_0+z)} \quad \text{(Eq. 2)}
\]

Where $u_*$ is the shear speed, $C_\mu$ is a model constant equal to 0.09, $K$ is the Von Karman’s constant equal to 0.43, $z_0$ is the aerodynamic roughness length, and $z$ is the reference height. The basic Atmospheric Boundary Layer conditions assigned at the inlet for this model include free stream speed ($U$; Eq. 3), turbulent kinetic energy (Eq. 1), and energy dissipation (Eq. 2; Richards and Norris, 2011).

\[
 U = \frac{u_*}{K} \ln \left( \frac{z^+ z_0}{z_0} \right) \quad \text{(Eq. 3)}
\]
A surface roughness ($z_0$) value of 0.002 was used during modelling, which is an estimate of surface roughness determined by Hebrard et al. (2012) from Mars Global Surveyor Thermal Emission Spectrometer rock abundance data for the study area.

Airflow results were obtained by conducting model runs using 5-meter cells of the topographic meshed surface. A simple grading in the $z$-direction was utilized to refine airflow turbulence closer to the surface as well as a refinement region, containing the Namib dune, which further refines the surface to 1-meter cells equal to the HiRISE DTM resolution. Additionally, to capture the enhanced crestline, an additional utility within OpenFOAM was used that extracts feature edges from the geometry surface and then explicitly specifies the features during meshing where points on the mesh boundary are attracted to the nearest points of the supplied feature edge. In this way, the airflow model successfully captures the detached flow from the Namib dune brink.

Model runs were conducted for sols 996 and 1238 using only reliable REMS data, excluding observations with wind sensor confidence levels affected by temperatures less than 50°C, electronic noise, rover movement, incorrect wind sensor configuration, and rear wind direction. Although REMS data was affected by the loss of two of the winds sensors, the wind data collected by the remaining sensor has been shown to be in good agreement with the Mars Regional Atmospheric Modelling System (Pla-Garcia et al., 2016). The remaining reliable wind data were averaged into hourly increments for modelling purposes (Table 1) to investigate changes in wind direction and magnitude throughout the martian day and to compare the two days of wind data from opposite seasons. Wind data was not collected late evening or early morning, spanning the hours between 18:00 to 8:00.
5.3 Results

5.3.1 Sol 996 ($L_s$ 348°)

Summer winds generally have a lower wind speed than winter winds and originate from the south (Fig. 4; Table 1). For sol 996, the greatest average speed recorded by REMS was 7.4 m s$^{-1}$ and occurred mid-afternoon around 15:00. REMS wind magnitudes at 9:00 and 18:00 are similar, having speeds of around 5.3 m s$^{-1}$. Modelled near surface winds on and around Namib dune range from 8.75 m s$^{-1}$ to 12.12 m s$^{-1}$ (Fig. 5). The greatest wind speeds are concentrated along the dune brink, where airflow travels up the lee slope then on to the stoss slope (Fig. 5). These elevated wind speeds along the dune brink generated surface shear stress values ranging from 0.007 kg m$^{-1}$ s$^{-2}$ in the late afternoon to 0.014 kg m$^{-1}$ s$^{-2}$ around midday (Fig 6).

Wind directions also varied throughout the sol. Between 9:00 and 12:00 winds were more southerly (Fig. 7) but around 13:00, wind direction began to shift to the east until about 17:00 when they began to shift south once again. The south easterly winds have a more pronounced effect on the Namib dune stoss slope, especially from times 15:00 to 17:00, where the near surface speeds and surface shear stress values are relatively elevated across much of the slope compared to other times of day (Fig. 5, 6, 7). The more southerly winds primarily affect the dune crest and upper lee slope, where the greatest values of wind speed and surface shear stress are generated (Fig. 5, 6, 7) compared to the more easterly winds. Throughout the day, none of the wind directions or magnitudes produced complex flow such as eddies and vortices (Fig. 7) during modelling. Airflow patterns are simple, following the topography with a few subtle diversions around the Namib dune (Fig. 6 and 7).
Figure 5. Near surface wind speed and wind vectors (black arrows) for every hour of sol 996 (southern summer L, 348°) as viewed from the west on the surface. Wind vectors indicate the direction of the wind incident to the Namib dune.
Figure 6. Surface shear stress values for every hour of sol 996 (summer) with wind direction represented by black arrows in the lower right of each box.
The greatest wind speed recorded by REMS for sol 1238 was 8.28 m s\(^{-1}\) and occurred early afternoon around 13:00 (Table 1). Wind speeds in the morning beginning at 9:00 had a greater magnitude than the modelled summer morning winds, where REMS recorded an average of 6.28 m s\(^{-1}\). Evening winds from 17:00 to 18:00 were more similar in magnitude to the summer winds having speeds of around 5 m s\(^{-1}\). The maximum near surface wind speed predicted by CFD modelling is 15.25 m s\(^{-1}\), coinciding with peak speeds measured by REMS at

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**5.3.2 Sol 1238 (L\(_z\) 102°)**

Figure 7. Speed streamlines showing flow over the Namib dune for sol 996 (summer) for each hour of the day.
13:00 (Table 1 and Fig. 8). Surface shear stress values were greater than those generated during the summer day (Table 1 and Fig. 9). Modelled surface shear stress values for sol 1238 were well above the threshold for grain movement from morning to late afternoon (09:00 – 17:00). The greatest values of surface shear stress on the Namib dune were located along the dune brink with much of the stoss slope also having elevated values of surface shear stress (Fig. 9).

Wind direction largely originated from the northwest and was the dominant wind direction for the majority of sol 1238 (Fig. 10). Based on surface shear stress, these northwest winds affected the entire Namib dune stoss and the western portion of the dune brink which had elevated values of surface shear stress compared to the rest of the dune (Fig. 9). At 9:00, the wind direction was more westerly which had a greater effect on the western flank of the Namib dune, coinciding with the secondary slipface slope of the dune (Fig. 9 and Fig. 10; Ewing et al., 2017). By 18:00, the origin of wind direction shifted to northeast (Fig. 10). This shift in winds resulted in the surface shear stress values along the secondary slipface to drastically decrease and the surface shear stress values on the eastern half of the stoss slope to become elevated (Fig. 9).

No significant flow separation and reattachment was predicted by the model for any of the wind directions or magnitudes throughout the winter day. However, large helices did form on the lee side of the Namib dune beginning at 10:00 and continuing through 17:00 (Fig. 10). These large helices formed via redirected flow around the western flank of the dune. When the winds were more westerly or easterly, the complexity of airflow decreased and these large helices disappeared.
Figure 8. Near surface wind speed and wind vectors (black arrows) for every hour of sol 1238 (winter) as viewed from the surface from the west. Wind vectors show the direction of the wind incident to the Namib dune.
Figure 9. Surface shear stress values for every hour of sol 1238 (winter) with wind direction represented by black arrows in the lower right of each box.
Both sol 996 and sol 1238 exhibit distinct patterns in wind speed during the day. As temperatures increase, wind speeds also increase. One significant difference between summer and winter seasonal patterns was the time in which peak wind speeds occurred during the day. In general, summer peak winds typically occurred later in the afternoon than winter winds (Fig. 11). Summer winds generally originate from the southeast (Fig. 4) and are lower in magnitude.
than the northerly winds of winter (Table 1). While summer winds are generally lower in magnitude and incident to the Namib dune slipface, they can still have an influence on sediment redistribution and impact ripple formation along the lee slope as well as ripple migration on the stoss slope. Dune activity threshold based on shear stress was estimated on Mars at Nili Patera to be $0.01 \pm 0.0015 \text{ kg m}^{-1} \text{ s}^{-2}$ (Ayoub et al., 2014). Threshold wind speeds have never been measured on Mars, however, in situ observation during the Namib dune campaign recorded subtle intra-sol grain movement during periods when REMS wind speeds were above $8.5 \text{ m s}^{-1}$ (Bridges et al., 2017). Grain movement at these wind speeds was extremely limited, typically resulting in grain ‘scrambling’ as opposed to unidirectional grain movement.

Figure 11. REMS wind data for sols 996 and 1238. Wind speed increases during the morning and peaks in the afternoon, decreasing again with the approach of the evening. Sol 996 (summer) winds peaked later in the afternoon around 15:00 compared to sol 1238 (winter) where wind speeds peaked around 13:00.
transport and it is estimated that average wind speeds above 10 m s\(^{-1}\) are required for consistent grain saltation (Bridges et al., 2017).

5.4.1 Sol 996 Aeolian Activity

The lowest wind speed used in CDF modelling averaged 4.83 m s\(^{-1}\) for summer REMS observations between 11:00 and 12:00 (Table 1). This wind speed produced elevated near surface wind speeds and a maximum surface shear stress value of 0.008 kg m\(^{-1}\) s\(^{-2}\) along the Namib dune brink (Fig. 5 and 6). Under these conditions, it is unlikely that any aeolian modification is occurring. Before 11:00, REMS wind speeds were slightly greater, having an average speed of 5.51 m s\(^{-1}\) (Table 1). These wind speeds generated surface shear stress values equivalent to or slightly above the threshold value for sediment movement (Fig. 6), suggesting that some grain movement may have taken place but it was likely not sustained for long periods of time. If grain movement did take place, it was confined to the dune brink, reversing sediment transport back onto the stoss slope but sediment on the lee and stoss slopes were likely unaffected.

The greatest summer wind speeds for sol 996 were recorded by REMS in the early afternoon and averaged 7.40 m s\(^{-1}\) between 13:00 and 14:00 (Table 1). This wind speed generated near surface wind speeds up to 12.12 m s\(^{-1}\) (Fig. 5), correlating to a maximum surface shear stress of 0.011 kg m\(^{-1}\) s\(^{-2}\) (Fig. 6), just above the threshold for grain movement. The greatest values of surface shear stress were predicted during 12:00 - 13:00, having a maximum value of 0.014 kg m\(^{-1}\) s\(^{-2}\), which may have resulted in more sustained sediment movement for
that hour of the day. The Namib dune stoss slope was largely unaffected in terms of surface shear stress except for portions of the eastern half of the dune, especially near the dune brink.

The stoss slope ripples form a ladder-back pattern (Fig. 3), where smaller impact-generated ripples are superimposed on the larger ripples that trend NW and NE (Lapotre et al., 2016; Ewing et al., 2017), however, summer is likely a time of very little modification to these aeolian features. Wind direction for sol 996 shifted to a more easterly origin around 13:00 (Fig. 7), which would have had a greater influence on the Namib stoss slope ripples except by that time of day, wind speeds had decreased and the surface shear stress values were below the threshold for grain movement. Alternatively, ripple migration may be maintained at lower wind speeds by brief gusts of wind and the development of self-sustaining saltation clusters that occur on Mars due to the lower gravity and reduced vertical drag from the thin atmospheric (Claudin and Andreotti, 2006; Almeida et al., 2008; Kok, 2010a,b; Kok et al., 2012; Sullivan and Kok, 2017).

5.4.2 Sol 1238 Aeolian Activity

Wind directions for the winter season generally originated from the north (Fig. 4), in contrast to the summer southerly winds. The lowest wind speeds for sol 1238 occurred late afternoon around 17:00, where the average speeds dropped to 5.18 m s^{-1} and the surface shear stress values were below the threshold for sediment movement (Fig. 9). Very little sustained grain movement is likely occurring on the Namib dune during this time at these wind speeds. It is probable that aeolian activity shuts down completely after ~18:00, similar to sol 996 as the wind speeds decrease with the approach of night time. Aeolian activity may begin earlier in the
day during sol 1238 when compared to sol 996 based on the greater wind speeds recorded at 9:00 by Curiosity. Sol 1238 average REMS wind speeds at 9:00 were 6.28 m s\(^{-1}\) (Table 1), corresponding to a maximum surface shear stress value of 0.012 kg m\(^{-1}\) s\(^{-2}\) (Fig. 9), suggesting some sediment movement is occurring. The maximum wind speed occurred between 13:00 and 14:00 with a REMS hourly-averaged speed of 8.28 m s\(^{-1}\), capable of generating maximum near surface wind speeds of 15.25 m s\(^{-1}\) (Fig. 8). These elevated wind speeds generated surface shear stress values well above the threshold with a maximum of 0.025 kg m\(^{-1}\) s\(^{-2}\) during this time of day (Fig. 9). Surface shear stress values remained above the threshold value for much of sol 1238 from 09:00 to 17:00. These elevated shear stress values were enough to affect the entire stoss slope, sufficient to activate ripple movement as well as generate prolonged rainfall and grainflow activity on the lee side of the Namib dune.

Wind direction for sol 1238 was consistently from the northwest throughout the day except for a sudden shift to the northeast at 18:00 (Fig. 10). Wind directions for 09:00 were more westerly, which may have influenced sediment redistribution and ripple movement along the western flank, or secondary slipface, of the Namib dune. The complex helical flow predicted by the model on the lee side of the dune between 10:00 and 18:00 may not have had a significant influence on sediment transport since the helical patterns were composed of low wind speeds of around 4 m s\(^{-1}\) or less (Fig. 10). More northerly winds that dominated sol 1238 appear to have had a greater effect on the western half of the dune brink line (Fig. 9 and Fig. 10), potentially producing more rainfall and grainflow activity for a longer period. Elevated values of near surface wind speeds and surface shear stress do not occur on the eastern half of
the dune brink line until wind direction shifts at 18:00 to a more easterly origin and by this time, aeolian activity is shutting down with lower evening wind speeds (Fig. 8, 9, 10).

5.4.3 Namib Aeolian Environment

Based on HiRISE-derived change detection, overlapping with the REMS dataset in this study, the most dynamic seasons for aeolian activity within the Bagnold dune field was spring and summer (Bridges et al., 2017). Active migration of the Namib dune to the southwest was also confirmed (Bridges et al., 2017), consistent with previous studies (Silvestro et al., 2013, 2016). Unfortunately, changes to the ripples on the Namib dune could not be confidently tracked due to their rapid migration rates (Bridges et al., 2017). Curiosity visited the Namib dune during late autumn and recorded minimal grain movement (Bridges et al., 2017).

Very little change was detected from HiRISE images during autumn and winter, suggesting that conditions are not conducive to aeolian activity. Winter winds should be favourable to aeolian transport and dune migration to the southwest but HiRISE observations contradict these modelling predictions. Early springtime wind conditions are similar to winter winds in direction and magnitude and much of the observed aeolian activity through satellite detection occurs during the spring. It is possible that during the autumn and winter seasons, aeolian activity is halted due to water frost condensation between sand grains (Martinez et al., 2016; Bridges et al., 2017). Rising temperatures in the Spring may eliminate induration from water ice or frost, reactivating aeolian processes. Geochemical precipitates can also affect aeolian activity, however, an extremely low volatile content was measured at the Namib dune during late autumn (Ehlmann et al., 2017) and potential geochemical precipitates in the form of
anhydrite composed less than 1.5 weight percent of the dune sediment (Achilles et al., 2017). Based on these results, sediment induration due to ice or salts seems unlikely.

One remaining explanation for the decreased aeolian activity during the winter may be due to dust infiltration (Jakosky and Christensen, 1986). Due to the effects of dust infiltration, the martian dust cycle may have a significant effect on seasonal and daily transport of aeolian sediment. Dust is typically injected during the southern spring when temperatures are rising along with wind speeds and settles during late southern summer and throughout the autumn season (e.g. Newman et al., 2002; Basu et al., 2004; Guzewich et al., 2017). Despite winter winds being conducive to grainfall and grainflow activity, these aeolian processes may be inhibited due to dust settling and insufficient wind velocities, which may need to exceed 15 m s\(^{-1}\) (Newman et al., 2002), to overcome the inter-particle cohesion of typical martian atmospheric dust estimated to be on the order of 1 μm (Toon et al., 1977; Pollack et al., 1995).

Lastly, summer may be a season of aeolian change, but perhaps not as rapid as during early spring. Model output suggests that sediment movement is minimal and confined to a short period of time during the day when wind velocities are the greatest. However, greater wind speeds occurred throughout the summer (Fig. 4) and may have initiated grain transport for longer periods. These southerly winds would transport sediment from the dune brink north on to the stoss slope, possibly resulting in a rounding of the brink line. Greater wind speeds originating from the southwest might drive the migration of the ladder-back stoss ripples. In addition, south westerly winds may be responsible for the formation of the lee slope impact ripples.
5.5 Conclusion

Typical seasonal wind conditions exhibited by sol 996 and sol 1238 corresponding the summer and winter seasons, respectively, were analysed using CFD airflow modelling to investigate effects of local topography on near surface winds and surface shear stress values on the Namib dune in Gale Crater, Mars. Hourly wind directions and magnitudes were modelled throughout each Mars day for both the summer and winter seasons, beginning at 9:00 and continuing through to 18:00 using data collected by Curiosity REMS (Table 1).

Summer winds typically originate from the southeast and are lower in magnitude than winter winds (Table 1). Modelling results of sol 996 suggest that very little aeolian transport occurs on a typical summer day with early-afternoon winds being the most influential having the greatest magnitude and surface shear stress values above the threshold for grain movement (Fig. 6). The south easterly summer winds appeared to affect the dune brink the most, potentially resulting in displacement of sediment on to the stoss slope and potentially smoothing the brink line (Fig. 5, 6, 7). These winds may also promote the formation and migration of the impact ripples across the lee slope as well as the ladder back ripples observed on the stoss slope.

Typical winter winds originate from the northwest and are sufficient to sustain prolonged aeolian activity throughout a typical winter day. Surface winds for sol 1238 beginning at 9:00 exceeded 11 m s\(^{-1}\) and peak surface wind speeds occurred at 13:00 reaching 15 m s\(^{-1}\) (Fig. 8 and Fig. 9), correlating to surface shear stress values well above the threshold for sediment movement. These winds speeds should be favourable to grain saltation but
concurrent HiRISE observations showed very little dune change during the autumn and winter seasons suggesting that something is preventing detectable grain saltation, grainfall, and slipface advancement.

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CHAPTER 6

Summary of findings and contributions
**Grainflow Morphodynamics**

This study was the first to introduce a classification of grainflow activity providing descriptions and comparisons of variations in grainflow planform morphology as well as flow thickness and volume estimates or redistributed sediment. The grainflow morphologies observed during data collection in the Maspalomas dune field include, slab flows, hourglass flows, funnel, and lobe flows. On average, grainflows were approximately 1 cm thick, ranging between 0.05 and 8 cm. Grainflow thickness increased downslope, where sediment accumulated at the base of the slipface, resulting in a wedge shape. Slab flows were rare but transported the greatest amount of material, averaging approximately 182,000 cm$^3$ or redistributed sediment per flow event. Hourglass grainflows occurred regularly and redistributed an average of approximately 22,000 cm$^3$ per flow event. Funnel and lobe flows were small, superficial flows that typically occurred in between larger grainflow events. These grainflows redistributed an average sediment volume between 1,000 and 2000 cm$^3$ per flow event.

Grainflow morphodynamics may be a reflection of the local wind regime, turbulent wind patterns on the slipface, sediment characteristics or other environmental factors such as salt or moisture content. A classification of grainflow morphologies enables comparative studies to take place across a range of aeolian environments and may also provide valuable insights into grainflow deposits preserved in the rock record. This classification will also be useful in interpreting aeolian environments and slipface dynamics on other planets.
Grainflow Classification Applied to a Martian Dune Slipface

Images captured by the Curiosity rover in front of the Namib dune on Mars provided a unique opportunity to directly compare terrestrial slipface grainflow dynamics to martian slipface dynamics. Aeolian signatures and grainflow activity were well-preserved on the martian dune enabling the terrestrial grainflow classification system from Chapter 2 to be applied which provided a means to surmise details about the aeolian environment and the most recent slipface activity. In addition, grainflow thicknesses were estimated for two of the freshest grainflows on the Namib dune using trigonometric calculations based on the shadow lengths cast by the flows and the sun’s elevation at the time the image was acquired. Grainflow thicknesses for the Namib dune appear to be thinner than those observed in the Maspalomas dune field. Despite the thinner flows, the Namib grainflows distributed equivalent volume amounts of sediment as the Maspalomas flows, which was attributed to differences in grainflow length.

Multiple hourglass grainflows were present on the Namib dune suggesting that the slipface experiences high energy events, capable of transporting large amounts of sediment from the stoss slope to the lee slope, thereby triggering several grainflow events that successfully transport sediment to the base of the slipface. The freshest grainflow were also hourglass morphologies along with a small number of lobe and funnel flows. Observations at the Maspalomas dune field occurred during high-magnitude winds and produced multiple hourglass grainflows and these flows were also accompanied by several lobe and funnel grainflows that preceded or followed the initiation of hourglass flows and the occasional slab flow. Very little evidence of lobe and funnel flows were identified on the Namib dune slipface
and those that were present were largely confined to just below the dune brink, suggesting a low wind energy incapable of depositing sediment mid slope to create localised over steepening. The Maspalomas slipface was also highly dynamic, where any evidence of previous grainflow activity was erased by rainfall before another grainflow occurred. The Namib dune slipface, in contrast, has multiple aeolian features preserved on the slope, including impact ripples that are crosscut by grainflow activity and tensional cracks, suggesting there was little to no rainfall to erase previous aeolian activity.

The rover visited the Namib dune during late autumn and according to HiRISE satellite monitoring, the autumn and winter seasons are a period of very little aeolian change. Aeolian activity occurred in the summer before Curiosity’s visit to the dune and the slipface may reflect aeolian activity experienced when winds originated from the southeast. These winds, being incident to the Namib slipface would be incapable of rebuilding the slipface slope from rainfall and initiating the large hourglass flows. Therefore, the hourglass grainflows require an alternative formation mechanism capable of transporting large amounts of sediment to the slipface in a low energy environment. As previously observed by Ewing et al. (2017), the actively migrating large stoss ripples on the Namib dune intersect the dune brink obliquely and can introduce sufficient amounts of sediment to the upper slipface slope to trigger grainflow as they migrate. This mechanism would also explain why lobe and funnel flows are confined to just below the dune brink with the continual introduction of sediment throughout the summer season.
Computational Fluid Dynamic Airflow Modelling of the Namib Dune, Gale Crater, Mars

Seasonal and daily simulations were conducted for the Namib dune to investigate the complex local airflow patterns responsible for the aeolian signatures present on the Namib dune stoss and lee slopes. These simulations constrained periods throughout the Mars year and day when the Namib dune is actively migrating and periods when the local winds (collected by the Curiosity rover) have a greater effect on ripple migration.

Seasonal airflow simulations of MY 33 suggest that the seasons most conducive to grainfall and slipface advancement due to grainflow activity are autumn, winter, and early spring. Each of these seasons had wind directions and magnitudes capable of generating complex airflow patterns on the lee side of the Namib dune, including flow separation at the dune brink, reattachment flow as well as steered flow helical flow. However, HiRISE images collected throughout that same mars year indicate that the Namib dune was immobile during the autumn and winter seasons and most active during spring and summer. The lack of slipface advancement during autumn and winter, despite wind direction and magnitude being favourable to grainflow activity, may be due to the presence of seasonal deposits of frost and ice that cement the top layer of sand grains. Although the wind directions are more southerly during late spring and throughout the summer, slipface advancement may still occur if sustained by stoss ripple migration. Large amounts of sediment may be introduced on to the slipface slope as the large stoss ripples obliquely intersect the brink. The addition of sediment from the stoss ripples results in localised over steepening in the absence of grainfall or grain saltation over the dune brink. This process may occur throughout the summer season but without a way to erase previous grainflow activity and restore the slipface slope, this
mechanism of grainflow activity would eventually terminate. This would explain the lack of grainfall evidence from the seemingly fresh aeolian signatures preserved on the slipface slope when the Curiosity rover visited Namib dune in late autumn. It is likely that the early spring is the primary time of the martian year when the slipface slope is rebuilt and most of the grainflow activity occurs.

Daily airflow simulations were conducted for a typical summer and winter day. Days from summer and winter were chosen to contrast airflow patterns from opposing wind directions at opposite times of the martian year. The summer season generally has lower magnitude winds than a typical winter day and winds originate from the southeast, as opposed to the northwest. Wind speeds increased during the morning for both the summer and winter day and peak sometime in the afternoon. For the winds during the summer day, this peak occurred around 12:00, whereas the peak wind speed for the winter day occurred around 15:00. Surface shear stress values derived from airflow simulations for the summer day suggested that very little aeolian transport occurred. The greatest values of surface shear stress were located along the Namib dune brink but during greater wind speeds and more easterly winds, the ladder back ripples on the stoss slope are likely actively migrating and introducing sediment on to the slipface. Wind speeds throughout much of the winter day were conducive to sediment transport, as indicated by surface shear stress values. After 16:00 surface shear stress values dropped below the threshold for grain movement as wind speeds decreased. Winds were primarily from the northwest throughout much of the day and generated helical flow patterns on the lee side of the dune. However, as revealed during investigations of seasonal airflow patterns, the winter is a time of little to no slipface advancement despite wind
directions and speeds being favourable to grainflow activity. The early spring season, when slipface advancement begins, is similar to the winter season in regards to wind direction and magnitude. Therefore, the wind patterns observed during the winter day are likely very similar to those experienced during early spring.

Future Research

The microscale CFD modelling results presented herein are a significant improvement to mesoscale modelling previously conducted for the martian aeolian environment in terms of spatial resolution. However, there are limitations to the model and uncertainties introduced from the dataset.

The movement of the Curiosity rover was, perhaps, the greatest source of uncertainty apart from the loss of the two wind sensors in this study. Ideally, wind data would have been collected from a stationary source where the effects of local topography could be minimal and/or consistent. Wind data scatter was evident in rose diagrams of REMS data but that scatter was minimized by seasonally averaging wind data (or selecting days of wind data less likely to be influenced by topography based on rover location) and validating the reliability of observed seasonal and daily trends with mesoscale model predictions. Due to these limitations, future missions to Mars focusing on meteorology or aeolian processes would significantly benefit from the installation of a stationary collection site.

A more attainable goal for future study of the martian aeolian environment would be the ability to incorporate time-dependent data allowing for the investigation of sudden gusts of wind and detailed changes in wind direction and speed. The ability to study the effects of gusts
of wind is especially important to the martian aeolian environment where the lower surface gravity and atmospheric pressure/drag results in the rapid formation of saltation clouds from the initial movement of only a few grains. In addition, the incorporation of time-dependent data would also be valuable for studying diurnal wind shifts unique to Gale Crater, where daytime winds generally originate from the north but increasingly adjust to more southerly winds as the evening approaches. To conduct a more detailed analysis of time-dependent wind speed and direction changes and the subsequent effects on sediment transport, a Large Eddy Simulation (LES) turbulence model is required. The computational cost of LES modelling can be significant but would be highly valuable in future studies of martian aeolian dynamics. LES modelling would further constrain seasonal times of sediment transport and improve estimates of bulk sediment migration but would be limited to the frequency of wind data collection as well as the changing location of the rover along its traverse.

**Overall Assessment**

In conclusion, this overall PhD study represents a major contribution to the current understanding of slipface processes, bedform-scale airflow dynamics and the martian aeolian environment regarding the categorization and quantification of grainflow types, turbulent airflow patterns modeled at 1 m resolution on Mars in relation to sand ripple response and alcove formation on a lee slope of a martian dune.