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Polar Eolian Sand Transport: Grain Characteristics Determined by an Automated Scanning Electron Microscope (QEMSCAN®)

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Abstract

QEMSCAN®, an automated scanning electron microscope, is used to provide a high-resolution analysis of eolian sands collected from Victoria Valley, McMurdo Dry Valleys, Antarctica. This technique provides a rapid, digital, quantitative morphological and mineralogical analysis of sediments, originally developed for the mining industry, which we apply for the first time to the study of eolian sand transport. Results show fine to medium-sized sands (<300 μm) are similar in shape and mineralogy throughout the hyper-arid landscape of the Victoria Valley. We relate this to the almost continuous mixing of fine-grained sediments in the mostly snow- and ice-free valley by frequent thermally induced easterly winds and less common but stronger topographically channeled southwesterly foehn winds. Analysis of local dune sands transported during easterly winds, which typically just exceed the local threshold entrainment velocity of 5.3 m s^{-1} (at 0.4 m), indicate preferential transport of quartz grains by these winds. Surface type was found to exhibit considerable influence over the characteristics of eolian sand transport with much larger grains carried in saltation and modified suspension above fluvio-glacial outwash surfaces than above sand dunes. Results illustrate the potential of QEMSCAN as an effective tool for multi-parameter analysis of eolian sands allowing greater insight into the controls on eolian sand transport in settings such as the Victoria Valley, Antarctica.

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Introduction

Cold climate eolian processes remain relatively understudied in comparison to their warm desert counterparts which have been the focus of extensive field and laboratory research for more than 100 years. As a result, knowledge of fundamental controls on the transport and deposition of sediments by the wind in cold climates remains equivocal (see reviews by Koster, 1988; McKenna Neuman, 1993; Seppälä, 2004). This arises from the limited understanding that currently exists on the influence of such factors as ice-marginal winds, greater air densities at low temperatures, and the presence of snow and ice on eolian systems in cold environments (McKenna Neuman, 1993).

The influence of low air temperature on particle entrainment and transport are attributed to differences in air density and the effect of air viscosity on drag and turbulence, the reduced amount of water vapor in the air, and the influence of inter-particle cohesion (McKenna Neuman, 2004). Sand transport rates at −40°C may be up to 70% higher than at a temperature of +40°C for the same wind speed (McKenna Neuman, 2004). Cold winds are also suspected to entrain larger grains than for equivalent wind speeds in warm environments. For example, Selby et al. (1974) reported grains of 3 mm in transport at a height of 2 m above the surface during wind speeds of 41 m s^{-1} and temperatures of −10°C in the McMurdo Dry Valleys, Antarctica. For entrainment of the same 3 mm grain, Selby et al. (1974) calculated a 10 m s^{-1} difference in threshold wind speed between the extreme temperature differences of Antarctica and subtropical deserts. Work by McKenna Neuman (2003) also showed that at lower temperatures the airstream had greater competence for eolian transport and, for a given wind speed, could potentially entrain grains with diameters up to 40–50% greater in size than at higher temperatures found in most subtropical deserts.

Snow and ice exert a considerable influence over the wind transport of sediments. Snow may effectively protect sediment from entrainment, while also acting as a sediment trap for any material in transport, forming niveo-eolian deposits (McKenna Neuman, 1993). Ice-bonding of sand grains also inhibits transport by the wind by increasing the inter-particle cohesive force which must be overcome by the fluid drag that is brought to bear on the surface by the wind. Under such conditions threshold entrainment velocities are much higher compared to dry surface sediments (van Dijk and Law, 1995; Seppälä, 2004). In cold and dry conditions, sublimation of surface ice can free surface grains, making them available for transport by the wind (McKenna Neuman, 1990; Van Dijk and Law, 1995, 2003). As temperatures approach 0°C, inter-particle ice bonds begin to thaw and associated evaporation and/or sublimation will dry surface sediments, thereby allowing entrainment of grains by the wind (McKenna Neuman, 1990; van Dijk and Law, 1995).

In cold climate settings significant differences commonly exist in grain size, shape, and sorting of sediments susceptible to entrainment by the wind compared to the mature eolian sands typical of most warm deserts (McKenna Neuman, 1993; Seppälä, 2004). Cold environments typically contain a wider assortment of particle sizes from deposits such as glacial till and glacio-fluvial outwash surfaces (e.g. Ahlbrandt and Andrews, 1978; McKenna Neuman, 1993; McGowan and Sturman, 1997; Mountney and

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Russell, 2004). The effects of cryogenic weathering on particle size and disintegration in cold environments are complex and poorly understood (French, 1996; French and Guglielmin, 2000). However, laboratory experiments in which quartz, amphiboles, and pyroxenes were exposed to repeated freeze-thaw cycles have shown that quartz grains are relatively unstable in cold climates (Minervin, 1982; Rogov, 1987 [cited in French, 1996]), in contrast to their relative stability under temperate and warm climate conditions.

Analysis of the physical attributes of eolian sediments in cold climate settings such as size, shape, and mineralogy and their influence on grain transport are rare, typically due to the time-consuming approaches to their analysis by manually point counting samples using optical microscopy or X-ray diffractometry (XRD) and fluorescence. As a result, few studies present all such information, but instead focus on one parameter such as particle size. However, recent technological advances have led to sedimentary analyses based on image analysis using, for example, automated scanning electron microscopy (SEM). This approach can return a multitude of digital morphological and mineralogical information on individual particles in one automated operation (Ehrlich et al., 1984; Petruk, 1989; Krinsley et al., 1998; Knight et al., 2002). The analysis scale of individual grains allows operation on small sample sizes and is ideal for eolian transport applications where often only very small samples are available for analysis. One application of automated SEM-based image analysis is QEMSCAN, a rapid quantitative mineral analysis system using a SEM fitted with digital pulse processors and light element X-ray Energy Dispersive Spectrum (EDS) detectors. The QEMSCAN system and interactive software is a new particle analysis technique originally developed for the minerals industry (previously known as QEM*SEM; see David et al., 1990; Sutherland and Gottlieb, 1991; Lätti, 1997; Gottlieb et al., 2000; Khosa et al., 2003; Goodall et al., 2005). Use of this technology has since expanded to broader environmental applications including fluvial geomorphology (e.g. Riley et al., 1989), soil and dust forensic geoscience (e.g. Pirrie et al., 2003) and sediment contamination identification (e.g. Pirrie et al., 2004). However, QEMSCAN has not yet been routinely adopted in eolian sand transport studies.

In this paper we present results from the application of QEMSCAN to the analysis of eolian sands from the Victoria Valley, Antarctica. The Victoria Valley contains an abundance of eolian deposits that have been the subject of several studies which described and mapped their distribution (e.g. Lindsay, 1973; Selby et al., 1974; Calkin and Rutford, 1974) and accumulation (Lancaster, 2002; Ayling and McGowan, 2006). Point counting using polarized light microscopy was applied to sands in the Victoria Valley region by Ayling (2001) and Wilson (2003). However, a detailed analysis of the sedimentological properties of eolian landforms in the Victoria Valley and their influence on grain transport has not previously been conducted. This study presents results from a high-resolution grain analysis applied to eolian polar sands sampled from surface deposits and saltation plumes above fluvio-glacial outwash surfaces and a barchan dune in the Victoria Valley.

Physical Setting

LANDSCAPE

The Victoria Valley is the northernmost of three large ice-free valleys (the others being the Wright and Taylor Valleys; Fig. 1a), collectively known as the McMurdo Dry Valleys (MDVs). The MDVs are situated in the Transantarctic Mountains, bounded by the McMurdo Sound/Ross Sea to the east and the East Antarctic Ice Sheet to the west. In the western end of Victoria Valley, five small valleys converge near Lake Vida, a 5-km-long perennially frozen lake which occupies a glacial curved trough. This is the topographic low point of the valley into which seasonally wet melt-streams flow from both west and east. East of Lake Vida, valley topography is more confined and trends in a southwest-northeast direction. The valley is bordered to the south by the Olympus Range with peaks exceeding 2000 m and to the north by the 1500-m-high St Johns Range. These ranges are comprised mainly of granite, granite-gneiss, and dolerite intrusive parent material (Calkin and Rutford, 1974).

The MDVs are believed to have remained essentially ice-free for much of the last 13.6 My (Sugden and Denton, 2004). Their barren exposed surficial sediments consist of glacial moraines, fluvio-glacial outwash fans, sand sheets, and dunes, all of which are subject to periglacial processes. The depth of the active layer below the surficial sediments typically increases from near zero in early November to 30–50 cm in late January (Conovitz et al., 2006). Although sedimentary landforms occur throughout the MDVs, the only area where significant eolian features occur is in the Victoria Valley between Lake Vida and the Victoria Lower Glacier (Fig. 1b) (Selby et al., 1974). These include sand sheets, several "whaleback dunes" or "whaleback mantles" (Selby et al., 1974; Calkin and Rutford, 1974) near Lake Vida, and the largest sand dune field in the Antarctic, near the terminus of the Packard Glacier (Fig. 1b). The dune field is comprised of barchan dunes and barchanoid ridges in a belt 4 km long and 0.5 km wide (Lindsay, 1973; Selby et al., 1974). Sediment in the dune field is believed to be sourced from fluvio-glacial outwash and weathering of exposed rock (Selby et al., 1974; Calkin and Rutford, 1974). The internal stratigraphy of the dunes reveals snow- and ice-cemented (niveo-eolian and denivation) layers (Lindsay, 1973; Selby et al., 1974). Despite cold-climate controls on sand transport and a reversing wind regime (see Speirs et al., in press), the dune field has displayed an average westward migration of 1.5 m yr^{-1} over the last 40 years (Burke et al., in press).

CLIMATE

The wind regime of the Victoria Valley is dominated by along-valley topographically channeled airflow. During summer, thermally generated easterly to southeasterly valley winds prevail. This circulation develops due to differential surface heating between the low-albedo, snow- and ice-free surficial sediments of the valley and the high-albedo glacier surfaces to the east, analogous to sea-breeze circulations (McKendry and Lewthwaite, 1990). In winter, wind direction is more variable but light northwesterlies dominate, punctuated by topographically modified southwesterly gales, believed to be foehn (Thompson, 1972; Clow et al., 1988; McKendry and Lewthwaite, 1990; Nylen et al., 2004; Ayling and McGowan, 2006). Onset of foehn events occur as an abrupt change of wind direction to the southwest with wind speeds often >30 m s^{-1}. These are associated with a significant warming of air temperature by as much as 50°C and a corresponding decrease in relative humidity. The most extreme temperature changes occur during winter when cold valley air is replaced by topographically modified foehn. These winds play a significant role in geomorphic processes in the Victoria Valley (Ayling and McGowan, 2006).

The MDVs receive little precipitation due to the influence of the Transantarctic Mountains which act as a barrier preventing moisture-bearing weather systems in the Ross Sea moving towards

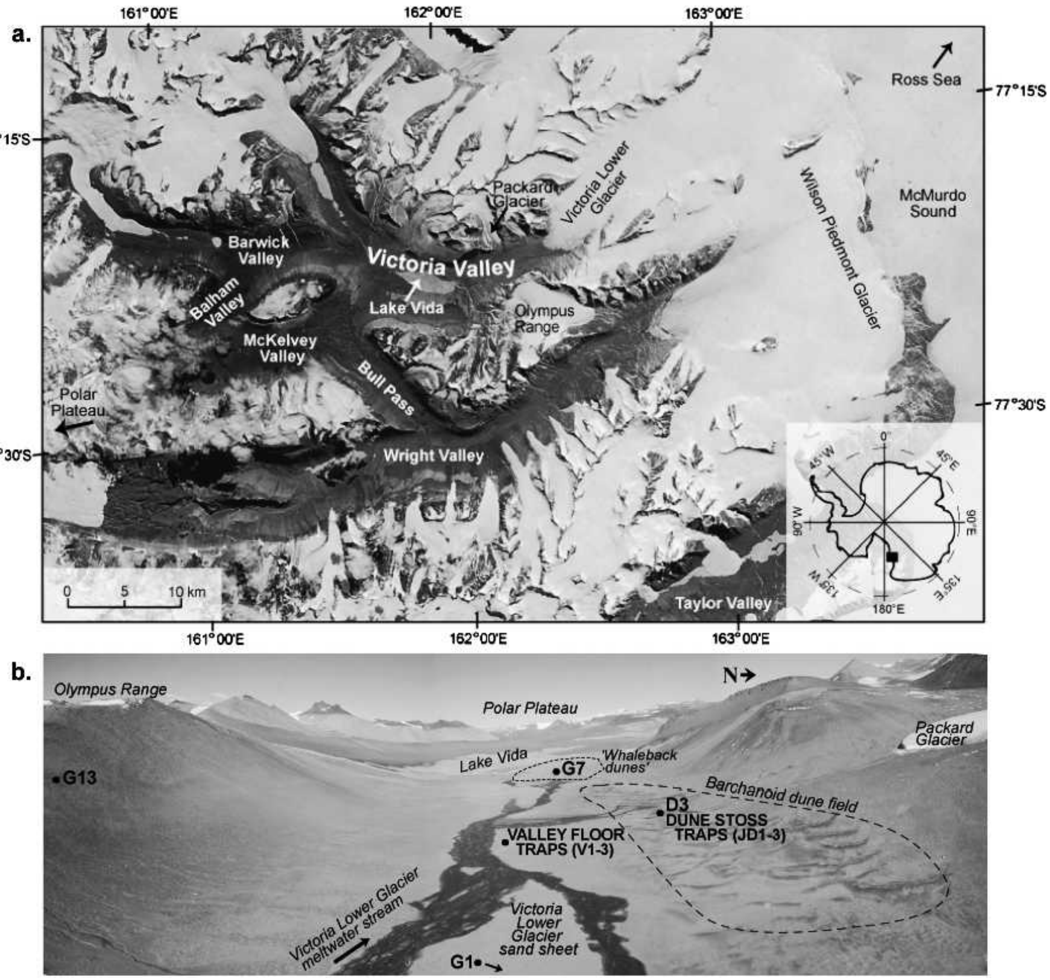

FIGURE 1. (a) Location of Victoria Valley, McMurdo Dry Valleys. (b) Oblique aerial photograph of Victoria Valley looking west towards the polar plateau. Approximate localities of sediment sampling sites listed in Table 1 are shown.

the MDVs (Mullen and Sinclair, 1990). No precipitation records are available for sites in the Victoria Valley, although annual snowfall at Lake Vanda (Wright Valley) is 10 mm water equivalent (Chinn, 1990). Average mean annual air temperature at Lake Vida is −27.4°C (1996–2004 data), with an average summer (NDJ) temperature of −4.6°C (range: −33.43°C to +9.98°C). During winter, mean winter (MJJ) air temperature at Lake Vida is −40.74°C (range: −65.47°C to +0.18°C).

Methods

FIELD SITES AND SAMPLING

The grain characteristics of 10 samples collected in the Victoria Valley during November/December 2004 were analyzed using a QEMSCAN system. Four of these samples were ''grab samples'' collected from sediment surfaces in the Lower Victoria Valley (Table 1; Figs. 1b and 2), while the others were collected from sand in saltation (eolian sand transport) using passive sand traps. All samples were collected during easterly valley winds, the dominant wind system during summer (Doran et al., 2002).

Eolian samples from the saltation cloud were collected by two sets of four wedge-shaped BSNE traps based on the design of Fryrear (1986), located on the stoss slope of a solitary barchan dune and over fluvio-glacial outwash deposits on the valley floor (Figs. 1b, 2e, 2f). This trap design was tested by Shao et al. (1993), who reported an overall sampling efficiency of 90 ± 5% for eolian sand-sized particles. Each of the four traps were attached to a pivoting wind vane and mounted at heights shown in Table 1. No sediment was collected in trap 4 positioned at 1.45 m above the surface during the sampling periods presented in this paper.

The dune surface sample (D3) and dune stoss sand trap samples (JD1-3) were collected on an isolated, active barchan dune located near the center of the Victoria Valley dune field (Fig. 2d). The dune was approximately 6.5 m high from the dune toe to the crest, with a slip-face height of 2 m, a length of 55 m, and a width of 50 m.

Local meteorological conditions were monitored using two HOBO^{TM} Weather Logger automatic weather stations (AWS), deployed in close proximity to the sand traps. These monitored wind speed at 0.4 m and 2.1 m above the surface with readings logged every 10 seconds. A Sensit^{TM} (piezoelectric saltation sensor) was mounted near the dune field AWS to monitor the onset, intensity, and cessation of saltation events.

SEDIMENT PREPARATION AND QEMSCAN ANALYSIS

All sediment samples were placed into labeled and sealed sample bags in the field and on return to the laboratory were oven-dried for 12 hours at 120°C before being split into subsamples for analysis by the QEMSCAN system (http://www.intellection.com.au/). QEMSCAN samples were split again using a spinning microriffler to obtain uniform 0.45 g samples. Graphite was then

TABLE 1

Location and site description of sediment samples analyzed using the QEMSCAN system.

Sample number	GPS location	Sample type	Site description
G1	S77.21.43.1, E162.21.11.0	surface	Sand sheet in front of Victoria Lower Glacier terminus
G7	S77.22.51.5, E162.05.56.7	surface	Ridge of whaleback feature
G13	S77.23.03.2, E162.16.48.1	surface	South valley wall — 305 m above valley floor
D3	S77.22.12.2, E162.12.24.0	surface	Dune stoss surface sand
JD1	S77.22.12.2, E162.12.24.0	saltation	Dune stoss trap 1: 0.13 m above dune surface 2 Dec 2004
JD2	S77.22.12.2, E162.12.24.0	saltation	Dune stoss trap 2: 0.40 m above dune surface 2 Dec 2004
JD3	S77.22.12.2, E162.12.24.0	saltation	Dune stoss trap 3: 0.75 m above dune surface 2 Dec 2004
V1	S77.22.31.8, E162.13.13.2	saltation	Valley floor trap 1: 0.11 m above valley floor 5 Dec 2004
V2	S77.22.31.8, E162.13.13.2	saltation	Valley floor trap 2: 0.34 m above valley floor 5 Dec 2004
V3	S77.22.31.8, E162.13.13.2	saltation	Valley floor trap 3: 0.70 m above valley floor 5 Dec 2004

added to these samples to provide a supporting matrix to minimize settling and segregation by density, and to ensure an even distribution of all grains when mounted for analysis. The sample/graphite mixture was shaken in a modified dental amalgam mixer for 12 seconds, ensuring random grain orientation. Samples were molded in a resin mixture and when set, the resin blocks were ground and polished. The samples were checked under an optical microscope to ensure random orientation and even distribution of grains. The QEMSCAN analysis is fast and can measure thousands of grains sequentially, thereby ascertaining a wealth of grain information even from very small samples. Between 895 and 2545 grains were analyzed per sample by the QEMSCAN system in this study. Output included grain mineralogy, size, and shape.

QEMSCAN uses EDS X-ray spectra to create digital grain images with mineralogy mapped at a user-defined resolution (10 μm in this study). Mineralogy was automatically determined by comparing the X-ray energy spectra to known chemical composition which was then assigned to standard mineralogical species. Standard density was also assigned to each mineral. Previous comparative studies demonstrate that mineralogy determined by QEMSCAN compares well to standard techniques. QEMSCAN has been shown to identify all major minerals detected by XRD in addition to a wider range of minor minerals

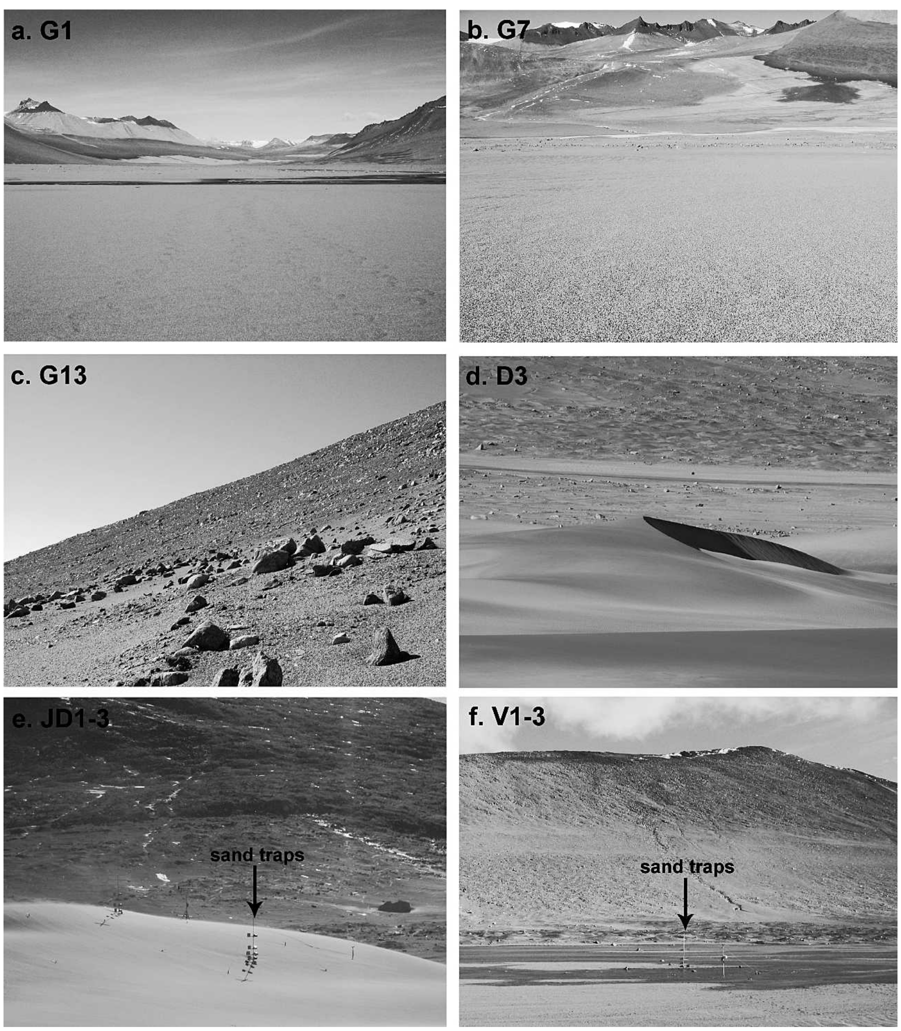

FIGURE 2. Sedimentary environments at sampling sites in Victoria Valley. For site descriptions, see Table 1.

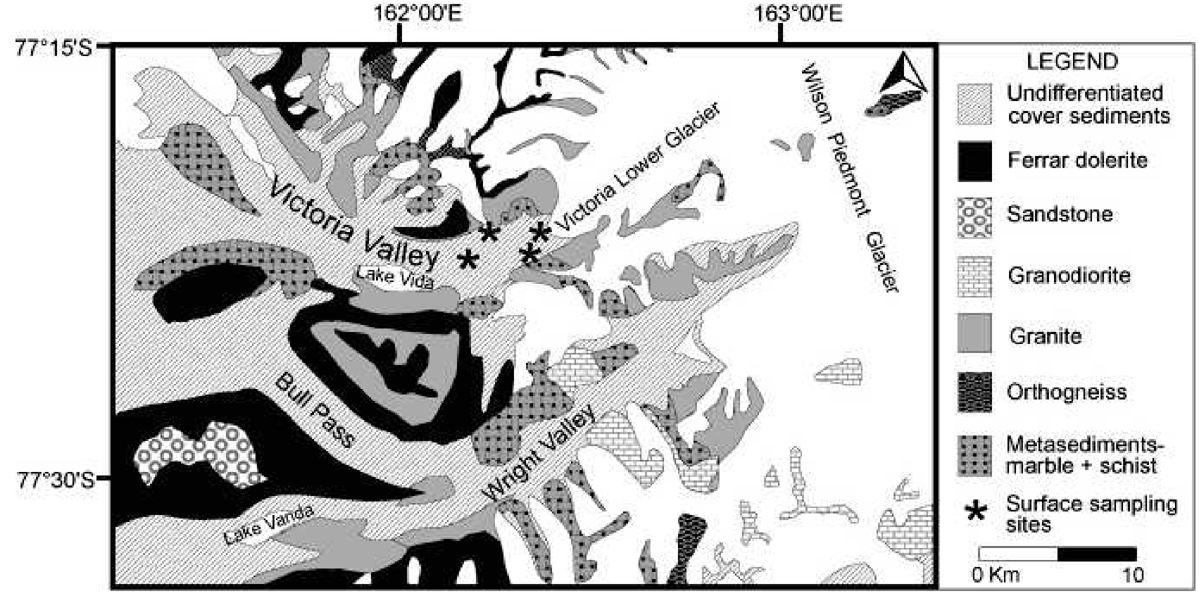

FIGURE 3. Geology of the Victoria Valley region (modified after Mortimer et al., 2001).

below the XRD detection limit (Goodall et al., 2005). The mineralogy of the Victoria Valley samples determined by QEMSCAN compare reasonably well with previous point-counting microscopic analyses in the region by Ayling (2001), Wilson (2003), and Ayling and McGowan (2006) despite different samples being analyzed. Importantly, identical minerals are identified using either technique. Additionally, QEMSCAN was able to differentiate between pyroxenes and amphiboles where previous microscopic attempts had encountered ambiguities.

Grain size was calculated by QEMSCAN using the "sectional size"—the average of the horizontal lengths of the particle image at a 10 μm resolution. As the sample preparation ensured random orientation of the grains, the horizontal lengths were also subject to random orientation and were not rotated or measured along the longest axis. It is assumed that particle shape does not significantly bias mean grain size given the random grain orientation and large grain population. Grain size information is based on the methods of Folk and Ward (1957) in the GRADISTAT (Blott and Pye, 2001) statistical package. For verification purposes, samples were dry-sieved and grain size information was calculated, also using GRADISTAT. There was insufficient sand mass in the fine fraction of the Victoria Valley samples to carry out wet sieving.

Grain shape was determined according to QEMSCAN's "shape-factor," which is the grain perimeter squared, divided by the grain area. A perfect circle (and sphere) using this method would have a shape-factor of $4\pi = 12.56$. A grain with a shape-factor <15 was termed well-rounded, 15–16 as rounded, 16–17 as subrounded, 17–18 as subangular, 18–19 as angular, and >19 as very angular. These intervals were selected such that the grain images of the QEMSCAN shape-factor classes correspond to the Powers (1953) roundness classes. Results of the QEMSCAN analysis were then queried and sorted based on desired grain properties. In this study we present analyses of size distribution against mineralogy and shape-factor.

Results

PHYSICAL CHARACTERISTICS OF FINE-GRAINED SURFACE SEDIMENTS

Results from the QEMSCAN analysis show that quartz, Ca.Fe.Mg silicate (clinopyroxene), and Al.Ca silicate (plagioclase feldspar) are the dominant minerals in the Victoria Valley surface samples, with smaller concentrations of Fe.Mg silicate (orthopyroxene) and Al.K silicate (potassium feldspar), reflecting the dominance of granite and Ferrar dolerite parent material in the valley (Figs. 3 and 4). Trace amounts of other silicates including Ti silicate, Al silicate, Al.Fe silicate, and other non-silicate minerals including Fe.Ti oxides, Fe oxides, zircon/xenotime, and calcite/dolomite were also found in surface sediment samples. Calcite and dolomite is present as small rounded grains and is thought to be remnants of the marble metasediments.

Grain size information for the QEMSCAN and dry sieve techniques are shown in Table 2. There is notable deviation in the mean grain size obtained between the two techniques. This is not surprising given that these techniques measure different aspects of grain size. Further comparative analysis of the two techniques is warranted; however, it is beyond the scope of this paper which will concentrate on the multi-parameter grain information from QEMSCAN and the associated implications for eolian transport processes.

The size distributions of the sampled surface sands (Fig. 5a) display markedly different patterns. Sand from the dune stoss slope (D3) is classified as medium sand, moderately well sorted with a mean grain size of 282 μm and has a finely skewed distribution. In comparison, the surface sample from the Victoria Lower Glacier sand sheet (G1) shows a bimodal grain size distribution, with a mode at 125 μm and a coarse grain surface lag >750 μm (mean grain size 377 μm). The bimodal distribution of surface sediment from sand sheets in the Victoria Valley was also observed by Calkin and Rutford (1974) and Selby et al. (1974) and is also a common feature to warm desert sand sheets (Kocurek and Nielson, 1986). Sediments from the crest of the whaleback dune (G7) were moderately sorted, with similar proportions of grains in the size classes between 100 and 700 μm and a discrete population of grains >775 μm forming the surface lag. The mean grain size of G7 is 494 μm. Sediments collected from site G13 on the valley wall were markedly finer (mean grain size of 163 μm) than the other surface samples.

Surface sediments from the dune stoss slope (D3) were found to contain the highest proportion of quartz (37% of sample) of all surface samples, which vary from 14% on the whaleback dune (G7) to 22% near the Lower Victoria Glacier (G1) and 23% on the

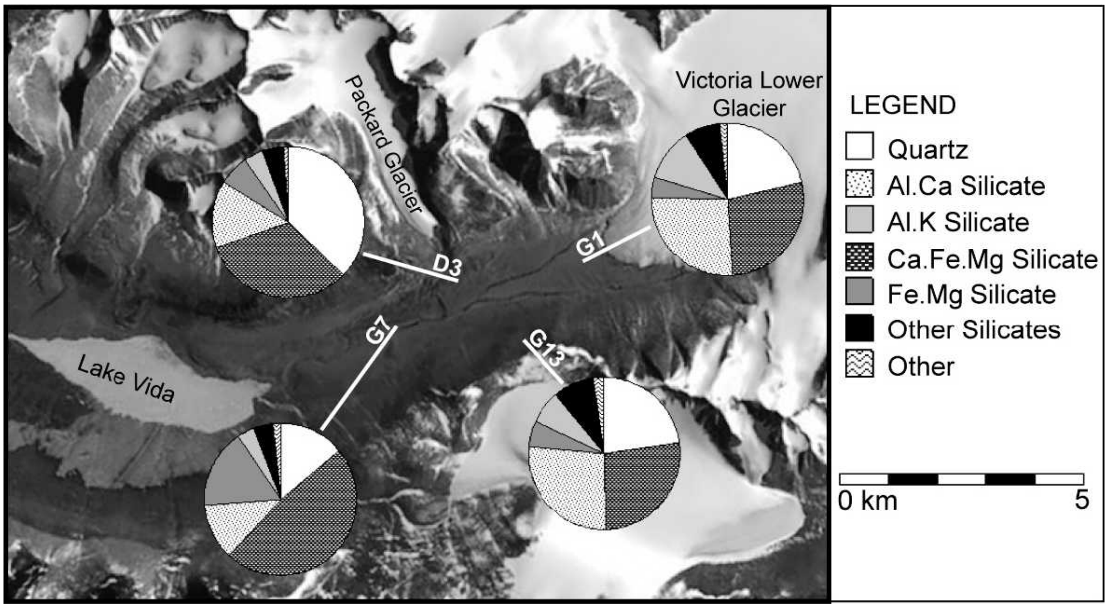

FIGURE 4. Mineralogy of fine-grained surface deposits in Victoria Valley.

valley wall (G13) (Fig. 4). This sample also displayed a marked increase in the dominance of quartz, decrease in Al.K silicate, and increase in grain roundness with grain size (seen in the mineral and shape distributions for D3 in Figs. 5b and 5c). This trend is also evident in samples G1 and G13 for grains <300 μm.

The mineralogy of G7 on the whaleback dune differed significantly from the other surface samples and had the greatest overall concentration of Ca.Fe.Mg silicate (48%), Fe.Mg silicate (17%), and the lowest concentration of quartz (14%) (Fig. 4). The mineralogy of G7 is similar between size classes, although the coarse-grained lag (>775 μm) contains particularly high concentrations (82%) of the dense Ca.Fe.Mg and Fe.Mg silicate minerals (density >3.3 g cm^{-3}). Hence, the coarse surface lag sediments of the whaleback sample are mostly comprised of dense, heavy minerals more resistant to eolian entrainment and transport. The coarse surface lag grains of G1 on the Victoria Lower Glacier sand sheet did not show such a dominance of heavy minerals in this size range, with only 35% of grains >775 μm consisting of Ca.Fe.Mg and Fe.Mg silicates. This is likely due to the greater distance to the source of these large and heavy grains, i.e. the Ferrar dolerite intrusions near Lake Vida (Fig. 3).

The fine sand-sized fractions (<300 μm) of all surface samples display similarities in terms of their shape and mineralogical characteristics with the shape-factors of grains in this size range being very well correlated between all samples (*r* values >0.9 [from multiple ANOVAs of the shape-factor between samples]). The mineralogy of these particles which are dominated by Al.Ca and Ca.Fe.Mg silicates and quartz is slightly less well correlated (*r* values ranging from 0.51 to 0.97 [from multiple ANOVAs of the mineralogical components between samples]). Notable is that each sample displays a similar trend in the distribution of grain size and mineralogy, indicating that grains <300 μm are from one population and have similar transport histories, most likely dominated by wind. Larger grains (>300 μm) did not show this consistency in roundness or mineralogy between samples.

DUNE SALTATION SAMPLES AND ASSOCIATED METEOROLOGY

Constant easterly valley winds with mean wind speeds of 5.1 m s^{-1} and gusts to 12.2 m s^{-1} (at 0.4 m) (Fig. 6) were observed over the barchan dune during the dune saltation

TABLE 2

Grain size information using Folk and Ward (1957) measures for MDVs surface and saltation samples by QEMSCAN and dry sieve techniques. Note: inadequate sample mass was available for dry sieving of several saltation samples.

	QEMSCAN				Dry sieve		
Sample	Particles measured (*n*)	Mean (μm)	Sorting (σ)	Skewness (*Sk*)	Mean (μm)	Sorting (σ)	Skewness (*Sk*)
G1	1712	377	2.254	−0.492	429	2.389	−0.483
G7	895	474	1.792	−0.420	468	1.967	−0.328
G13	2545	163	1.955	+0.047	147	1.829	+0.088
D3	1536	282	1.524	−0.196	251	1.397	−0.109
JD1	2357	216	1.420	−0.171	205	1.283	−0.124
JD2	2442	229	1.511	−0.139	—	—	—
JD3	2544	172	1.483	−0.169	—	—	—
V1	2408	280	1.685	−0.056	218	1.492	+0.087
V2	1154	334	1.493	−0.232	295	1.446	−0.087
V3	1150	410	1.571	−0.369	—	—	—

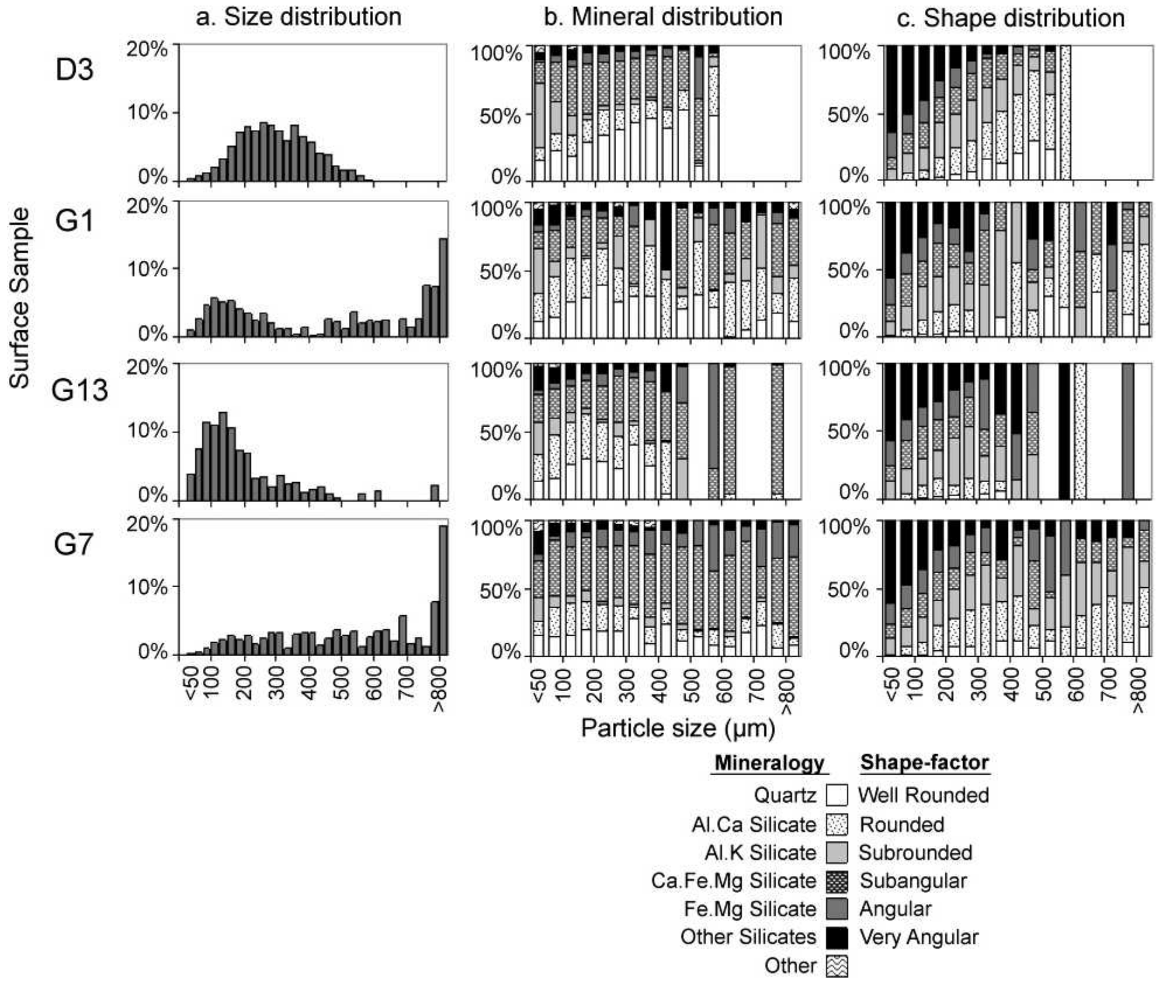

FIGURE 5. Grain characteristics of surficial sediments from the dune stoss slope (D3), Victoria Lower Glacier sand sheet (G1), valley wall (G13), and a whaleback dune (G7): (a) Size distribution; (b) mineral distribution; and (c) QEMSCAN shape-factor distribution.

sampling period. Despite 24 hour solar insolation at this latitude during summer, a diurnal cycle is still observed in the easterly valley winds, with lower wind speeds monitored during the early morning when the valley floor is shaded by the Olympus Range. During sampling over the dune, water vapor content of the easterly winds displayed a rising trend due to the increasing influence of a moist air mass. This moist air mass became established over the MDVs several hours after sampling and was associated with low cloud and graupel. Mean air temperature for the sampling period was $-3.5°C$, and air density averaged 1.60 kg m^{-3} (range 1.15 to 2.11 kg m^{-3}), with higher values recorded near the end of the sampling period.

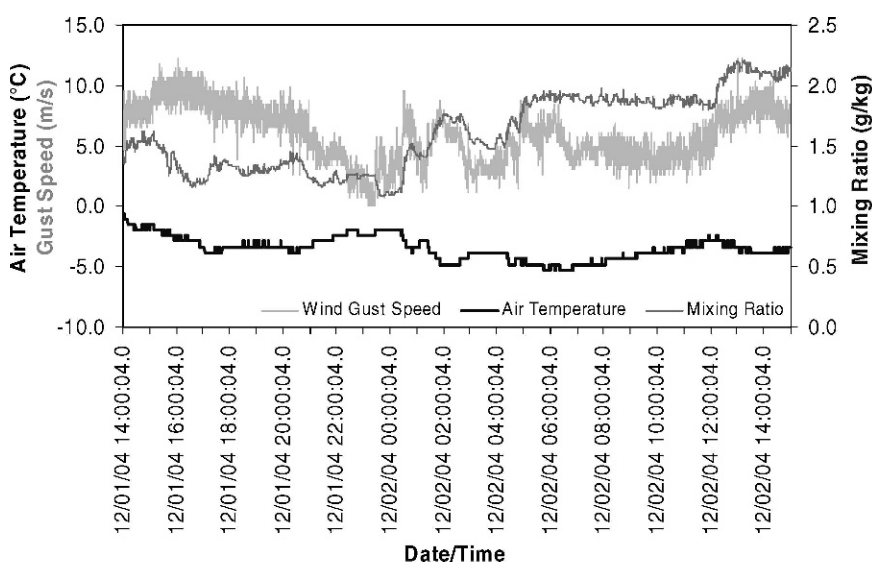

FIGURE 6. Local meteorological conditions monitored in the dune field during the dune saltation sampling period.

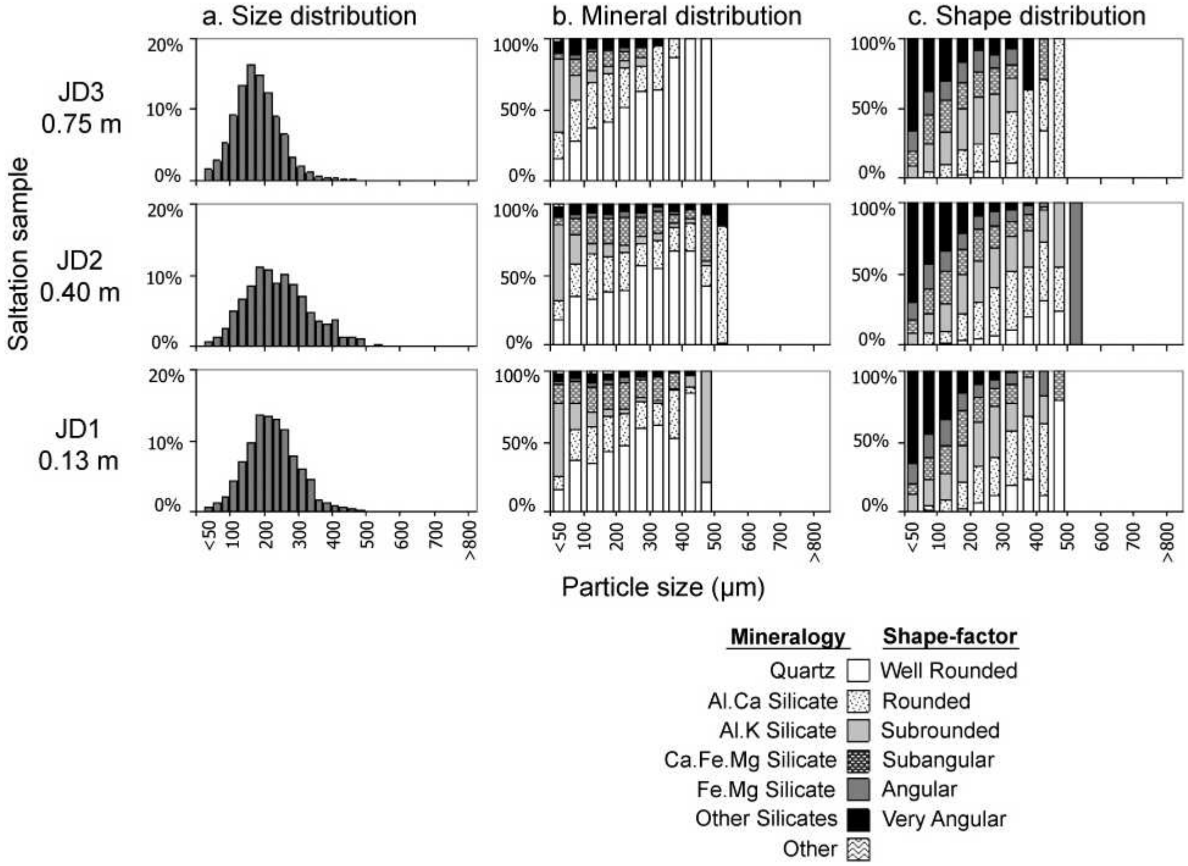

FIGURE 7. Grain characteristics of eolian sediments entrained above the dune stoss: (a) Size distribution; (b) mineral distribution; and (c) QEMSCAN shape-factor distribution.

The threshold entrainment velocity (u_t) required to initiate saltation over the study dune, monitored by the Sensit during easterly valley winds was 5.3 m s^{-1} (± 0.21 m s^{-1}) at 0.4 m above the surface. Wind gust speed exceeded u_t for 49.6% of the dune saltation sampling time. Streamwise sand flux was estimated at 0.01 kg m^{-2} h^{-1} between the limits of 0.11 m and 1.5 m above the dune stoss surface. QEMSCAN analysis of sand samples collected at 0.13 m, 0.4 m, and 0.75 m above the surface identified them to be predominantly rounded, moderately well sorted, and with a finely skewed size distribution (Fig. 7; Table 2) similar to the source sand D3. Mean grain size was 216 μm at 0.13 m (JD1), 229 μm at 0.4 m (JD2) and 172 μm at 0.75 m (JD3) above the dune stoss surface. Hence, an overall decrease in mean grain size with sampling height was observed in the dune field.

The dune saltation samples (JD1–3) contain the greatest concentrations of quartz within all the Victoria Valley samples, with an average of 46% quartz. This is a significant increase from the 37% quartz content of the dune stoss surface sand (D3) and 22% quartz content on the lower Victoria Glacier sand sheet (G1). The second highest mineral concentration is Al.Ca silicate with 25%, which also increases in content from the dune stoss surface sample (15%). Ca.Fe.Mg silicate content decreases from the

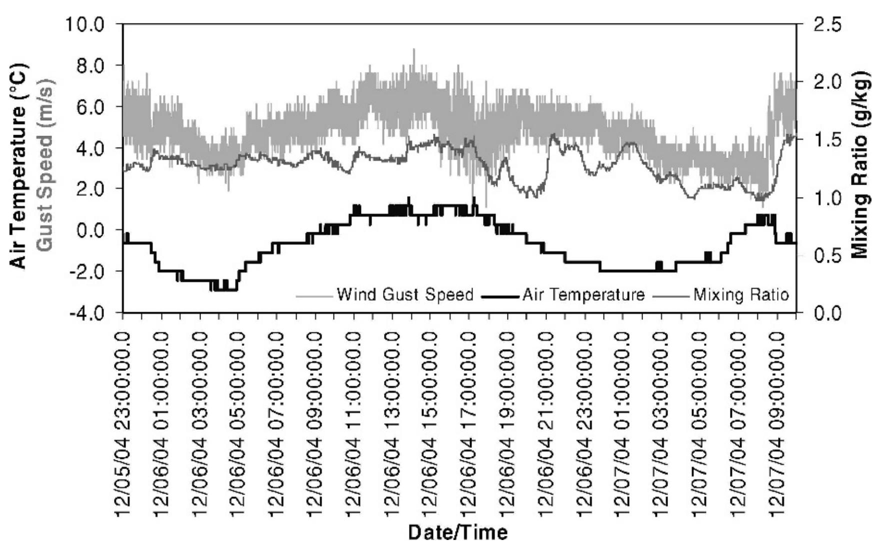

FIGURE 8. Local meteorological conditions monitored on the valley floor during the saltation sampling period. Consistent easterly winds were monitored during this period.

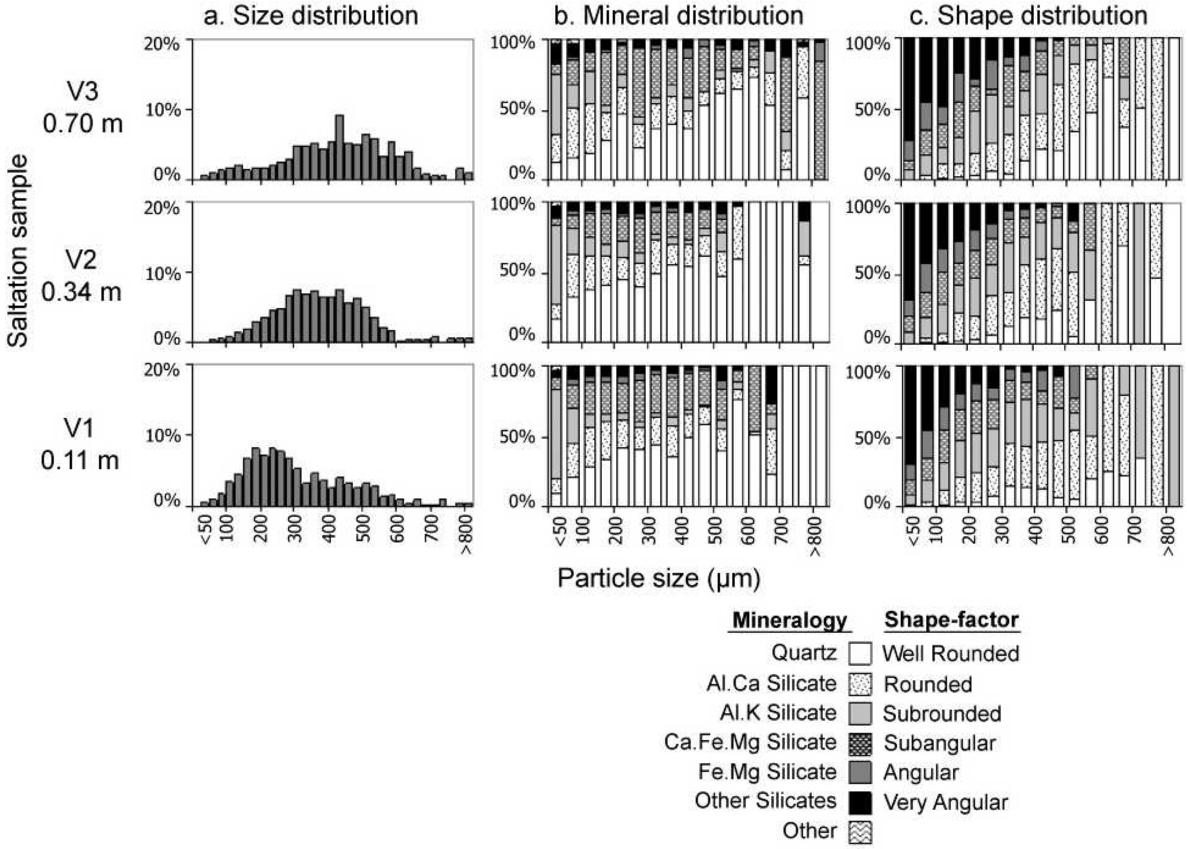

FIGURE 9. Grain characteristics of eolian sediments entrained above the valley floor: (a) Size distribution; (b) mineral distribution; and (c) QEMSCAN shape-factor distribution.

surface (32%), with only 14% in transport above the dune stoss. Al.K silicate comprised 7% of the overall mineral content in the dune saltation samples and is the dominant mineral in the <50 µm size fraction. Fe.Mg silicate contributed to only 2% of the average mineral content in the dune saltation samples, with the remaining minerals comprised of the other silicates (6%) and other minerals (1%).

The saltation samples show a distinct increase in grain roundness and quartz content with grain size (Fig. 7). Overall quartz concentrations remained relatively constant with height above the surface, although the percentage of quartz in the medium sand-sized grains (250–500 µm) increased from 56% to 82% between 0.13 m and 0.75 m above the dune surface. A corresponding decrease in heavy minerals (Ca.Fe.Mg and Fe.Mg silicates) occurred in the large grain sizes with height, comprising only 2% of the coarser size fraction (250–500 µm) at 0.75 m. This suggests that a balance exists between grain mass (size and density) with height in the saltation cloud above the dune stoss, whereby larger grains are more likely to be less dense (and more rounded) quartz minerals. Grains <125 µm displayed little change in mineralogy with height, indicating that the properties of these fine grains are better mixed with height.

VALLEY FLOOR SALTATION SAMPLES AND ASSOCIATED METEOROLOGY

Sampling of the saltation plume over the fluvio-glacial outwash deposits was also conducted during easterly valley winds with a mean wind speed of 5.6 m s^{-1} and gusts to 9.14 m s^{-1} (Fig. 8). Winds were very dry with low mixing ratio values, and wind speeds displayed a pronounced diurnal cycle with maximum wind speeds monitored between 14:00 and 15:00 NZDT. Mean air temperature for this period was -0.7°C and a mean air density of 1.36 kg m^{-3} (range 1.07–1.65 kg m^{-3}). Streamwise sand flux was approximately 1.06 kg m^{-2} h^{-1} between the sampling heights of 0.11 m and 1.5 m above the valley surface.

Sediments collected from the airstream above the fluvio-glacial sediments of the valley floor were found to be larger (medium-sized sand) and less sorted than those in the dune field (Fig. 9a). Mean grain size was 280 µm at 0.11 m (V1), 334 µm at 0.34 m (V2), and 410 µm at 0.70 m (V3) above the surface (Table 2). This trend of increasing mean grain size with height above the valley floor surface is opposite to the fining of sediments with height measured above the dune stoss slope.

Similar to the dune field, quartz dominated the mineral content of the saltation cloud on the valley floor, averaging 46%. Ca.Fe.Mg silicate content was slightly greater than the dune field with 21%. Al.Ca silicate had the third highest concentration in these samples, averaging 17% followed by Al.K silicate with 7%. Fe.Mg silicate comprised 3% of the average mineral content, while other silicate minerals averaged 5%, and other non-silicates contributed only 1%. The general trend of increasing quartz grain content and grain roundness with grain size is also present in the valley floor saltation samples. Quartz concentrations were greatest at V2 (0.34 m), particularly in the larger grain sizes with 78% of grains >500 µm comprised of quartz. The coarser grains in saltation at V3 (0.7 m), however, showed less dominance of quartz with several heavy mineral (Ca.Fe.Mg) grains in transport. These large grains in transport at 0.7 m were also predominantly rounded, with 88% of grains >500 µm and 100% of grains >700 µm displaying rounded and well-rounded shape-factors.

Discussion

VALLEY-WIDE DISTRIBUTION OF FINE-GRAINED SEDIMENT

Analyses of surficial sediment samples collected from the Victoria Valley show that the sand size grains <300 μm of all surface samples displayed significant similarities in particle shape and mineralogy. These fine-grained sediments, which are predominantly angular, appear well dispersed throughout the Victoria Valley. In conditions of low air temperatures and associated higher air density, these fine-grained sediments <300 μm are transported on an almost daily basis during summer when they are blown west by the persistent easterly valley winds. The less frequent but stronger southwesterly foehn gales rework this sediment in an eastward direction during summer and probably intermittently during winter. Furthermore, these fine sands may also be transported in summer meltwater streams that flow from the Victoria Lower and Packard Glaciers west to Lake Vida. These streams typically flow for 4–12 weeks a year (Lyons et al., 2003; McKnight et al., 1999) and towards the end of summer as these streams freeze, the deposited sands become susceptible to eolian transport where they can be dispersed by the wind throughout the valley, even to heights at least 300 m above the valley floor. We believe that strong southwesterly foehn events are responsible for transporting fine-grained sediments (<300 μm) to these heights by suspension from the valley floor (or alternatively, along the sidewalls at these heights). Thermally driven easterlies are less likely to suspend sediment at significant heights as they are typically shallow winds, decreasing in strength with height (McKendry and Lewthwaite, 1990) and therefore, sediment transport capability. This was observed during field research under easterly conditions, whereby workers on the valley walls experienced almost calm conditions while stronger easterlies prevailed on the valley floor.

Foehn winds are also responsible for the deposition of fine-grained sediments (<125 μm) on the Victoria Lower Glacier, where the analyses of snowpit sediment samples by Ayling and McGowan (2006) identified feldspars as the most commonly occurring mineral comprising 40% on average, followed by quartz with 21% and pyroxene averaging at 15%. These mineral proportions compare well to the fine-sand-sized (<125 μm) fractions in surface samples collected from the Victoria Valley presented here, particularly G13, which had 43% feldspar (Al.Ca and Al.K silicates), 18% quartz, and 24% pyroxene (Ca.Fe.Mg and Fe.Mg silicate) content in this size range of grains. Only westerly foehn winds are capable of transporting sediment to the Victoria Lower Glacier, hence the close similarity between snowpit samples and G13 further suggests a foehn origin for fine-grained sediment at 300 m above the valley floor.

As foehn events in the Victoria Valley are associated with the higher wind speeds, we believe that the coarse surface lag grains present on fluvio-glacial outwash surfaces in the valley (e.g. G1) and on the whaleback dunes (e.g. G7) are transported and deposited during these events, particularly in winter when air temperatures during the initial stages of foehn onset may be less than −30°C. The associated greater air densities coupled with strong winds and the sublimation of surface ice would allow entrainment and transport of such large grains. Once deposited, these large grains through time would form a coarse-grained lag as finer sediments are winnowed from the deposits during the lower wind speeds typical of summer conditions. Pebble ripples in the MDVs described by Selby et al. (1974) are also likely to form during winter foehn events.

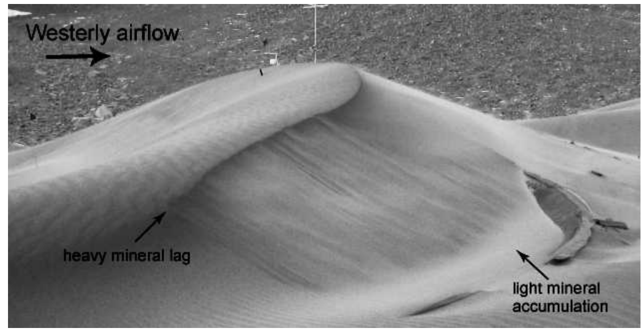

FIGURE 10. Evidence of preferential mineral selection during eolian transport. The less dense quartz (and similar density) minerals are transported over the crest and caught behind an exposed ice-cemented layer. The denser, heavy minerals are deposited along the crest line.

Results from the analysis of surface sands from the whaleback dune display markedly different size, shape and mineralogical characteristics compared to other surface samples collected from the Victoria Valley. Importantly, they show poor sorting of the sediments in the size classes <775 μm which is an uncharacteristic feature of dune sands and more resemblant of subglacial or fluvial deposition. Recent internal stratigraphy studies however, indicate that these features are in fact of eolian origin (Jol et al., 2007).

QUARTZ ENRICHMENT

Preferential entrainment of light quartz and feldspar minerals was seen in the saltation samples compared to surface sand in the Victoria Valley dune field. This left a visible lag of dark colored heavy mineral grains (Ca.Fe.Mg and Fe.Mg silicates) on the surface of the dunes as shown in Figure 10. Similar selective transport of light mineral grains has been observed during eolian transport of beach sands on the Dutch coast by de Meijer (1998) and on the Florida coast by Donoghue and Greenfield (1991). Mineral sorting by the wind probably occurs when wind speed is close to the threshold entrainment velocity which, coincidentally, is close to the mean daily wind speed during summer under easterly conditions. These thermally driven valley winds lack sufficient energy to entrain the denser grains consisting of Ca.Fe.Mg and Fe.Mg silicates (pyroxenes).

Additionally, analysis of surface sands from the Victoria Valley identified an enrichment of quartz grains in the dune field compared to other surface deposits in the valley. Quartz enrichment of dune sand in comparison to source area sediment is a characteristic common to many of the world's warm desert dune fields (Muhs, 2004). Muhs (2004) reviewed 5 possible explanations for this enrichment which included: (1) inheritance from a quartz-rich source sediment; (2) chemical weathering of feldspars in the source sediment region; (3) fluvial size reduction of feldspars; (4) loss of feldspars from chemical weathering within a dune field during long periods of dune stability; and (5) loss of feldspars by abrasion or ballistic impacts within a dune field during long periods of activity. Of these possible causes for quartz enrichment, we believe that the fifth explanation seems the most plausible as sand transport in the Victoria Valley sand dunes is regularly active except for several months each year during winter, when wind speeds do not exceed the local threshold entrainment velocity (except for winter foehn events), or when snow covers the dunes. At other times, the dune sands are highly mobile. Furthermore, our results show the preferential eolian entrainment of quartz minerals compared to heavy minerals. As the dune field is an accumulation of eolian sediments, it would be expected to contain this observed higher proportion of quartz sediment that has been preferentially entrained and transported by the wind during the summer.

Despite the high quartz concentration in the dune field, surface sediments in the Victoria Valley still contain a very high heavy mineral content compared to most eolian systems with pyroxenes averaging 42% of the total mineral content of the surface samples. Many warm desert dunes such as those in the Kalahari and Namib deserts of Africa, the Jafuruh sand sea in Saudi Arabia, the Great Sandy Desert in Australia, and several North American dune fields all contain an excess of 90% quartz (Muhs, 2004). Inactive cold climate settings such as the former periglacial environments in Central Europe also typically display >90% quartz (Seppälä, 1971, 2004). However, in active cold climate eolian environments, mixed-mineral sands are more common as sediments are often first-cycle weathering products from fluvio-glacial or beach material and have not been subjected to recycling and weathering leading to quartz dominance (Seppälä, 2004). Some active dunes in Finnish Lapland also contain a high heavy mineral content, averaging 34.6% by weight of sand (Seppälä, 1971). In the Victoria Valley, active weathering of granite and dolerites by fluvio-glacial processes, salt weathering, and eolian abrasion provides a continual input of first cycle mixed-mineral fine-grained sediment available for transport by the wind. Despite low denudation rates in the MDVs (Summerfield et al., 1999), these sediments remain and accumulate in the Valley due to the alternating wind regime and closed valley geometry, but are occasionally transported to distances such as the Victoria Lower Glacier and Wilson Piedmont Glacier during infrequent south-westerly foehn wind storms (Ayling and McGowan, 2006).

SURFACE CHARACTERISTICS

Surface composition played a significant role in the characteristics of eolian sands carried by the airstream in the Victoria Valley. Sands sampled from the saltation plume on the dune stoss slope show a slight decrease in mean grain size with height, which is typical of eolian sand transport. This sorting of grain size with height reflects the reduced capacity of the airstream to entrain and lift larger and heavier grains above the surface resulting in larger and denser grains being transported closer to the bed. Conversely, eolian sediments transported along the valley floor showed an atypical increase in mean grain size with height, and were less sorted with a wider range of grain sizes present. We attribute this to differences in surface characteristics between the valley floor and dune field. The non-erodible and elastic nature of the valley floor, comprised of frozen coarse-grained surface lags, pebbles, boulders, and larger glacial erratics would prompt a more efficient ballistic rebound of saltating particles from surface roughness elements in comparison with the soft dune surfaces. As a result, larger grains are carried to greater heights above the valley floor surface, as also observed by McGowan and Sturman (1997) over mid-latitude alpine fluvio-glacial deposits. The large sand grains collected at 0.7 m above the valley floor in the Victoria Valley were mostly rounded to well-rounded. This indicates that shape selection is also occurring, whereby large rounded grains are transported to greater heights due to their more efficient rebound from roughness elements on the valley floor. This is consistent with Williams' (1964) wind-tunnel experiments which showed spherical grains tended to bounce higher than angular grains. Even though the QEMSCAN shape-factor is effectively a measure of the roundness of a two-dimensional particle plane, not a three-dimensional object (sphere), sphericity and roundness are interrelated in the sense that the shape-factor of a sphere would also fall into the well-rounded shape-factor class.

Interestingly, the large rounded grains sampled at 0.7 m above the valley floor surface were not solely comprised of quartz, with several large heavy mineral particles present including Ca.Fe.Mg silicates. This indicates that although quartz may be preferentially entrained by the airstream due to its low density, large rounded heavy minerals are still capable of reaching large rebound heights over reflective surfaces even at wind speeds that just exceed threshold. These large grains collected at the 0.34 m and 0.7 m sampling heights were most likely transported during the strongest and most turbulent winds of the sampling period. However, the majority of the valley sampling period experienced wind speeds closer to u_t, resulting in the bulk of sediment (predominantly fine to medium sand-sized) transported close to the valley floor.

Sand flux between 0.11 m and 1.5 m above the valley floor was over 40 times greater than in the dune field despite similar wind speeds. This may be attributed to differences in surface characteristics as non-erodible surface roughness elements can increase turbulence intensity and promote sediment entrainment and transport (Nickling and McKenna Neuman, 1995). Elastic grain/bed collisions may also have resulted in more rapid transport, increasing the sand flux above the valley floor (Bagnold, 1941; Nickling and McKenna Neuman, 1995). Additionally, differences in meteorological conditions between the sampling periods may have contributed to the differences in sand flux. In spite of slightly higher air density during the dune sampling period, the cooler and moister conditions that prevailed were observed to cause a cohesive consistency of the dune sands which we infer as inter-particle cohesion by the capillary force of cooled surface moisture or ice-bonding upon freezing. This suggests that sediment supply may be limited during such conditions, effectively increasing the threshold entrainment velocity (e.g. Namikas and Sherman, 1995). During the valley floor sampling period, however, air temperature was higher with lower humidities, indicating that inter-particle ice-bonding of grains may not have been as important.

Conclusion

Analysis of fine-grained surface sediments and eolian sands from the Victoria Valley, Antarctica by QEMSCAN has identified trends and features in eolian sediment often masked under standard sedimentary analysis techniques. Surface sediments collected in the eastern end of Victoria Valley reveal that particles <300 μm are well correlated in respect to shape and mineralogy. This is believed to be the result of long-term mixing of fine-grained sediment caused by the alternating wind regime in Victoria Valley—a process that may have been going on for millennia, creating a widely dispersed population of fine-grained sediments with similar mineralogical and shape characteristics. Strong winds during foehn events are believed to deposit these fine-grained sands on the valley walls up to heights exceeding 300 m above the valley floor. Foehn events are also believed responsible for transporting much larger coarse grains and pebbles.

Sediments in the dune field sample are classified as medium-sized sands, moderately well sorted and predominantly comprised of quartz with heavy minerals such as the Ca.Fe.Mg silicates and Fe.Mg silicates. The dune field sands were enriched by low density and predominantly rounded quartz grains compared to other surface deposits in the valley. These quartz grains were also dominant in the saltation cloud compared to surface sand samples, suggesting that quartz grains are preferentially transported by the wind in Victoria Valley.

Analysis of samples collected from the airstream above a dune stoss slope and the fluvio-glacial deposits on the valley floor demonstrated the influence of surface characteristics on grain transport. Saltating sand grains above the dune surface exhibited a decrease in grain size with height, while above the valley floor they showed an increase in grain size with height up to 0.7 m above the surface.

Our results illustrate the potential of QEMSCAN as an effective tool for multi-parameter analysis of eolian sands. Further comparative analyses are warranted between the grain size results of QEMSCAN and standard sedimentological techniques. Importantly, however, QEMSCAN allows for relatively quick determination of grain attributes such as mineralogy (grain density) and its association with grain size and shape which is not often reported by eolian process-based studies. As a result, it has considerable potential for identifying grain attributes and their association with controls on the entrainment-transportation and deposition of fine-grained sediments by the wind, particularly in situations where only small samples are available.

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References Cited

Ahlbrandt, T. S., and Andrews, S., 1978: Distinctive sedimentary features of cold-climate eolian deposits, North Park, Colorado. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 25: 327–351.

Ayling, B. F., 2001: Dust accumulation on the Victoria Lower Glacier and Wilson Piedmont, coastal South Victoria Land, Antarctica, and its potential as a paleowind indicator. Unpublished honours thesis. Victoria University of Wellington, Wellington, New Zealand.

Ayling, B. F., and McGowan, H. A., 2006: Niveo-eolian sediment deposits in coastal South Victoria Land, Antarctica: indicators of regional variability in weather and climate. *Arctic, Antarctic, and Alpine Research*, 38(3): 313–324.

Bagnold, R. A., 1941: *The Physics of Wind Blown Sand and Desert Dunes*. London: Methuen.

Blott, S. J., and Pye, K., 2001: GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26: 1237–1248.

Burke, M. C., Ewing, R., Finnegan, D. F., and McGowan, H. A., in press: Sand dune movement in Victoria Valley Antarctica. *Geomorphology*.

Calkin, P. E., and Rutford, R. H., 1974: The sand dunes of Victoria Valley, Antarctica. *The Geographical Review*, 64: 189–216.

Chinn, T. J., 1990: The Dry Valleys. *In* Hatherton, T. (ed.), *Antarctica the Ross Sea Region*. Wellington: Department of Scientific and Industrial Research, 137–153.

Clow, G. D., Mckay, C. P., Simmons, G. M., and Wharton, R. A., 1988: Climatological observations and predicted sublimation rates at Lake Hoare, Antarctica. *Journal of Climate*, 1(7): 715–728.

Conovitz, P. A., MacDonald, L. H., and McKnight, D. M., 2006: Spatial and temporal active layer dynamics along three glacial meltwater streams in the McMurdo Dry Valleys, Antarctica. *Arctic, Antarctic, and Alpine Research*, 38(1): 42–53.

David, D., Jackson, R., and Wilke, G., 1990: QEM*SEM and the evaluation of the WIM 150 Mineral sands prospect. *In* Petruk, W., Hagni, R. D., Pignolet-Brandom, S., and Hausen, D. M. (eds.), *Process Mineralogy IX*. Las Vegas: The Minerals, Metals and Materials Society, 219–225.

De Meijer, R. J., 1998: Heavy minerals: from 'Edelstein' to Einstein. *Journal of Geochemical Explorations*, 62: 81–103.

Donoghue, J. F., and Greenfield, M. B., 1991: Radioactivity of heavy mineral sands as an indicator of coastal transport processes. *Journal of Coastal Research*, 7: 189–201.

Doran, P. T., McKay, C. P., Clow, G. D., Dana, G. L., Fountain, A. G., Nylen, T., and Lyons, W. B., 2002: Valley floor climate observations from the McMurdo Dry Valleys, Antarctica, 1986–2000. *Journal of Geophysical Research*, 107(D24): 4772, doi: 1029/2001JD002045.

Ehrlich, R., Kennedy, S. K., Crabtree, S. J., and Cannon, R. L., 1984: Petrographic image-analysis. 1. Analysis of reservoir pore complexes. *Journal of Sedimentary Petrology*, 54: 1365–1378.

Folk, R. L., and Ward, W. C., 1957: Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27: 3–26.

French, H. M., 1996: *The periglacial environment*. 2nd edition. Singapore: Longman, 341 pp.

French, H. M., and Guglielmin, M., 2000: Cryogenic weathering of granite, northern Victoria Land, Antarctica. *Permafrost and Periglacial Processes*, 11: 305–314.

Fryrear, D. W., 1986: A field dust sampler. *Journal of Soil Water Conservation*, 41: 117–120.

Goodall, W. R., Scales, P. J., and Butcher, A. R., 2005: The use of QEMSCAN and diagnostic leaching in the characterisation of visible gold in complex ores. *Minerals Engineering*, 18: 877–886.

Gottlieb, P., Wilkie, G., Sutherland, D., Ho-Tun, E., Suthers, S., Perera, K., Jenkins, B., Spencer, S., Butcher, A., and Rayner, J., 2000: Using quantitative electron microscopy for process mineralogy applications. *JOM*, 52(4): 24–25.

Jol, H. M., Bristow, C. S., Augustinus, P., and Wallis, I., 2007: The 'whaleback' dunes of Victoria Valley, Antarctica: a ground penetrating radar perspective. *Geological Society of America Annual Meeting*.

Khosa, J., Manuel, J., and Trudu, A., 2003: Results from preliminary investigation of particulate emission during sintering of iron ore. *Mineral Processing and Extractive Metallurgy*, 112: 25–32.

Knight, R. D., Klassen, R. A., and Hunt, P., 2002: Mineralogy of fine-grained sediment by energy-dispersive spectrometry (EDS) image analysis—A methodology. *Environmental Geology*, 42: 32–40.

Kocurek, G., and Nielson, J., 1986: Conditions favourable for the formation of warm-climate aeolian sand sheets. *Sedimentology*, 33: 795–816.

Koster, E. A., 1988: Ancient and modern cold-climate eolian sand deposition: a review. *Journal of Quarterly Science*, 3(1): 69–83.

Krinsley, D. H., Pye, K., Boggs, S., and Tovey, N. K., 1998: *Backscatter Scanning Electron Microscopy and Image Analysis of Sediments and Sedimentary Rocks*. Cambridge: Cambridge University Press.

Lancaster, N., 2002: Flux of eolian sediment in the McMurdo Dry Valleys, Antarctica: a preliminary assessment. *Arctic, Antarctic, and Alpine Research*, 34: 318–323.

Lätti, A. D., 1997: The application of QEM*SEM to the Quelimane heavy minerals deposit, Mozambique. *In* Robinson, R. E. (ed.), *Heavy Minerals 1997*. Johannesburg: South African Institute of Mining and Mineralogy, 197–202.

Lindsay, J. F., 1973: Reversing barchan dunes in Lower Victoria Valley, Antarctica. *Geological Society of America Bulletin*, 84: 1799–1806.

Lyons, W. B., Welch, K. A., Fountain, A. G., Dana, G. L., Vaughn, B. H., and McKnight, D. M., 2003: Surface glaciochemistry of Taylor Valley, southern Victoria Land, Antarctica and its relationship to stream chemistry. *Hydrological Processes*, 17: 115–130.

McGowan, H. A., and Sturman, A. P., 1997: Characteristics of aeolian grain transport over a fluvio-glacial lacustrine braid delta, Lake Tekapo, New Zealand. *Earth Surface Processes and Landforms*, 22: 773–784.

McGowan, H. A., Neil, D., Dowideit, G. R., and Speirs, J. C., 2005: Uncovering a polar dune field's response to climate variability. Poster presented at the Antarctica New Zealand Annual Conference, July 4–6, University of Canterbury.

McKendry, I. J., and Lewthwaite, W. D., 1990: The vertical structure of summertime local winds in the Wright Valley, Antarctica. *Boundary-Layer Meteorology*, 51: 321–342.

McKenna Neuman, C., 1990: Role of sublimation in particle supply for aeolian transport in cold environments. *Geografiska Annaler. Series A, Physical Geography*, 72(3/4): 329–335.

McKenna Neuman, C., 1993: A review of aeolian transport processes in cold environments. *Progress in Physical Geography*, 17: 137–155.

McKenna Neuman, C., 2003: Effects of temperature and humidity upon the entrainment of sedimentary particles by wind. *Boundary-Layer Meteorology*, 108: 61–89.

McKenna Neuman, C., 2004: Effects of temperature and humidity upon the transport of sedimentary particles by wind. *Sedimentology*, 51: 1–17.

McKnight, D. M., Niyogi, D. K., Alger, A. S., Bomblies, A., Conovitz, P. A., and Tate, C. M., 1999: Dry Valley streams in Antarctica: ecosystems waiting for water. *Bioscience*, 49: 985–995.

Minervin, A. V., 1982: The role of cryogenic processes in forming loess deposits. *Problems in Cryolithology*, 10: 41–61 (in Russian).

Mortimer, N., Forsyth, P., and Turnball, I., 2001: *Basement geology of the Wilson Piedmont Glacier*. Dunedin, New Zealand: Institute of Geological and Nuclear Sciences, unpublished geological map.

Mountney, N. P., and Russell, A. J., 2004: Sedimentology of cold-climate aeolian sandsheet deposits in the Askja region of northeast Iceland. *Sedimentary Geology*, 166: 223–244.

Muhs, D. R., 2004: Mineralogical maturity in dunefields of North America, Africa and Australia. *Geomorphology*, 59: 247–269.

Mullen, A. B., and Sinclair, M. R., 1990: Climate and weather. *In* Hatherton, T. (ed.), *Antarctica the Ross Sea Region*. Wellington: Department of Scientific and Industrial Research, 98–115.

Namikas, S. L., and Sherman, D. J., 1995: A review of the effects of surface moisture content on aeolian sand transport. *In* Tchakerian, V. P. (ed.), *Desert Aeolian Processes*. London: Chapman and Hall, 269–293.

Nickling, W. G., and McKenna Neuman, C., 1995: Development of deflation lag surfaces. *Sedimentology*, 42: 403–414.

Nylen, T. H., Fountain, A. G., and Doran, P. T., 2004: Climatology of katabatic winds in the McMurdo Dry Valleys, Southern Victoria Land, Antarctica. *Journal of Geophysical Research*, 109: D03114, doi: 03110.01029/02003JD002927.

Petruk, W. (ed.), 1989: *Image Analysis in Earth Sciences*. Ottawa: Mineral Association of Canada.

Pirrie, D., Power, M. R., Rollinson, G., and Camm, G. S., 2003: The spatial distribution and source of arsenic, copper, tin and zinc within the surface sediments of the Fal Estuary, Cornwall, UK. *Sedimentology*, 50: 579–595.

Pirrie, D., Butcher, A. R., Power, M. R., Gottlieb, P., and Miller, G. L., 2004: Rapid quantitative mineral and phase analysis using automated scanning electron microscopy (QemSCAN); potential applications in forensic geoscience. *In* Pye, K., and Croft, D. J. (eds.), *Forensic Geoscience: Principles, Techniques and Applications*. London: Geological Society, 219–225.

Powers, M. C., 1953: A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, 23: 117–119.

Riley, S. J., Creelman, R. A., Warner, R. F., Greenwood-Smith, R., and Jackson, B. R., 1989: The potential in fluvial geomorphology of a new mineral identification technology (QEM*SEM). *Hydrobiologia*, 176/177: 509–524.

Rogov, V. V., 1987: The role of gas liquid intrusions in mechanism of cryogenic disintegration of quartz. *Vestnik, Moscow University, Geography*, 3: 81–85 (in Russian).

Selby, M. J., Rains, R. B., and Palmer, R. W., 1974: Eolian deposits of the ice-free Victoria Valley, Southern Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics*, 17: 543–562.

Seppälä, M., 1971: Evolution of eolian relief of the Kaamasjoki-Kiellajoki river basin in Finnish Lapland. *Fennia*, 104: 1–88.

Seppälä, M., 2004: *Wind as a Geomorphic Agent in Cold Climates*. Cambridge: Cambridge University.

Shao, Y., McTainsh, G. H., and Leys, J. F., 1993: Efficiencies of sediment samplers for wind erosion measurement. *Australian Journal Soil Research*, 31: 519–531.

Speirs, J. C., McGowan, H. A., and Neil, D. T., in press: Meteorological controls on sand transport and dune morphology in a polar desert: Victoria Valley, Antarctica. *Earth Surface Processes and Landforms*.

Sugden, D. E., and Denton, G. H., 2004: Cenozoic landscape evolution of the Convoy Range to Mackay Glacier, Transantarctic Mountains: onshore to offshore synthesis. *Geological Society of America Bulletin*, 116: 840–857.

Summerfield, M. A., Stuart, F. M., Cockburn, H. A. P., Sugden, D. E., Denton, G. H., Dunai, T., and Marchant, D. R., 1999: Long-term rates of denudation in the Dry Valleys, Transantarctic Mountains, southern Victoria Land, Antarctica based on in-situ-produced cosmogenic ^{21}Ne. *Geomorphology*, 27: 113–129.

Sutherland, D. N., and Gottlieb, P., 1991: Application of automated quantitative mineralogy in mineral processing. *Minerals Engineering*, 4(7–11): 753–762.

Thompson, C. D., 1972: Climate of the Dry Valley area of South Victoria Land. *In* Stokes, E. (ed.), *Proceedings of the Seventh New Zealand Geography Conference*. Hamilton: New Zealand Geographical Society, 259–265.

van Dijk, D., and Law, J., 1995: Sublimation and aeolian sand movement from a frozen surface: experimental results from Presqu'ile Beach, Ontario. *Geomorphology*, 11: 177–187.

van Dijk, D., and Law, J., 2003: The rate of grain release by pore-ice sublimation in cold-aeolian environments. *Geografiska Annaler*, 85A: 99–113.

Williams, G., 1964: Some aspects of the eolian saltation load. *Sedimentology*, 3: 253–256.

Wilson, N., 2003: The movement and origin of the sand dunes in the Victoria Valley, Antarctica. Unpublished honours thesis. Victoria University of Wellington, Wellington, New Zealand.

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