Dust Production by Sand Grain Impact during Aeolian Saltation: An Experimental Study

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This work has not been previously submitted for a degree or diploma in any university. To the best of my knowledge and belief, the dissertation contains no material previously published or written by another person except where due reference is made in the dissertation itself.

Christa Pudmenzky
5 June 2003

The work performed by the winds in the atmosphere appears hardly to have received its due share of attention.

(Udden, 1894: 318)

ABSTRACT

This study focuses on the potential for aeolian abrasion of natural dune sands to produce fine dust particles. Particular attention is given to how the particle size, sorting, colour, shape and the presence of iron oxide coatings and clay skins affect the rate of dust production. Natural dune sand samples were obtained from the crests of active continental dunes from the Simpson Desert and the Channel Country and abraded for 72 hours using a large glass ‘test-tube’ chamber. The chipping, spalling and breakage of sand grains and the removal of iron oxide coatings and clay skins from grain surfaces produced between 0.41-0.98 % fine particles. Statistical analysis identified that the degree of sorting and grain roundness of a sand sample are the major influences on the dust production rate. Well-sorted, sub-rounded sand samples yielded less dust than poorly sorted angular sand grains. Comparison with previous studies of aeolian abrasion of crushed quartz sands, these natural dune sands produced very low quantities of fine material, but the widespread geographical distribution of desert dune fields makes them potentially a significant source of dust-sized particles on a global scale.

ACKNOWLEDGEMENTS

I would like to thank my supervisors, Associated Professor Grant McTainsh and Dr Andrew Hammond. Their advice, patience, support and encouragement were never ending. Many thanks go also to Dr Joanna Bullard of Loughborough University, UK for her support and advice. Emails can bridge any distance.

I am appreciative of many people who have been listening to my ‘dusty’ talk for the past two years. Craig Strong and Alex Pudmenzky were always there to ‘bounce off’ new ideas. When the generators producing the air for the experiments were not cooperating, Werner Ehrsam came to the rescue. Accesses to microscopic and photographic equipment were kindly made available by Jacinta Zalucki and Scott Byrnes. To get a real close-up view of my ‘bouncing grains’ I have to thank Loc Van Duong of the Analytical Electron Microscopy Facility, Faculty of Science, at Queensland University of Technology. Alex Creagh, the “stats guru” made sure that I was on the right track and Kenn Tews would be there when computer related problems posed a challenge.

Finally, I would like to thank my husband Alex. You have been by my side and supported me during these past two years. Do you now understand why I get excited about ‘dust’? Your knowledge of Matlab is invaluable. Thank you for writing the Matlab tool for grain recognition. Your proof reading is also very much appreciated.

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CHAPTER 1

INTRODUCTION

1.1 An overview of aeolian processes

Aeolian processes are important geomorphic processes and play a major role in the evolution of arid and semi-arid landscapes. The deflation of arid and semi-arid sediments and erosion of agricultural soils, expansion of deserts, dust storms and hazes, soil formation and ocean sedimentation are some of the geomorphic outcomes associated with aeolian processes (Goudie, 1978; Mooney, 1999). Aeolian processes have a range of environmental consequences including possible effects on climate, ocean sedimentation, soil formation, groundwater quality, crop growth, glacier ice quality, human health, damage to property and threat to live stock (Choun, 1936; Bryson and Barreis, 1967; Idso, 1976; Levin *et al.*, 1996; Tegen *et al.*, 1997; Arimoto, 2001). Globally, total dust emissions are estimated to about 3 000 Mt per year (Shao, 2000). Large quantities of mineral and organic matter are carried together with dust particles and redistributed around the world (Duce *et. al.*, 1991; Tegen and Fung, 1995; Shao, 2000). Many contaminants including heavy metals, pesticides, dioxins and radionuclides, that pose deleterious effects to human health and the environment, are associated with dust (Shao, 2000).

Aeolian processes are responsible for the movement, sorting and shaping of earthy materials in the landscape (Butler and Churchward, 1983). The most familiar products of aeolian processes in Australia are dunes, but the dust component is less familiar and more widespread. It has been estimated that over the last 500 000 years, millions of tonnes of dust have been removed by wind action from arid and semi-arid areas, and deposited downwind in continental Australia and farther beyond (Greene *et al.*, 2001). Large dust storms are a common phenomenon in Australia. Records date back to the 1900's (Liversidge, 1902; Chapman and Grayson, 1903). The dust storm of the 23rd of October 2002 was the largest dust storm recorded in the last 30 years. Strong north-westerly winds moved across western New South Wales and the Queensland Channel Country producing a dust band 1 500 km long, 400 km wide and extending 2.5 km into the atmosphere (Figure 1-1). Visibility was reduced to a few hundred meters (Figure 1-2). During this event tens of millions of tonnes of topsoil were removed from central Australia.

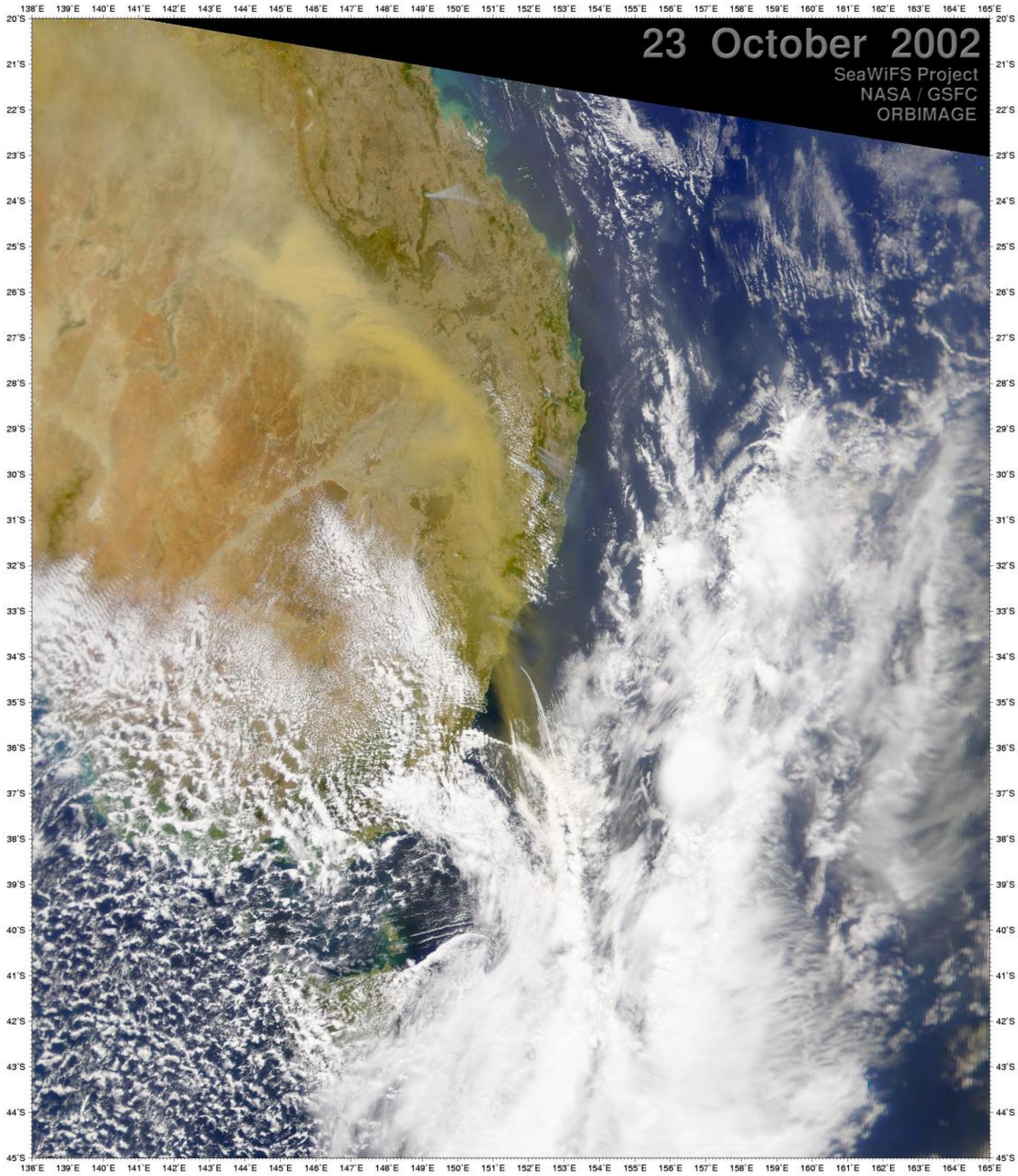


Figure 1-1: Dust storm event passing over eastern Australia on the 23 October 2002.

(source: Seawifs, 2002)

Figure 1-2: Dust storm engulfing the town of Griffith, NSW.

(source: McMillan, 2002)

In Australia, land degradation has taken place for millions of years but with European settlement 200 years ago the rate of anthropogenically induced land degradation has outstripped that of environmental processes (McTainsh and Boughton, 1993). Excessive land clearing of native vegetation, overgrazing and inappropriate agricultural practices has resulted in increased frequency and intensity of wind erosion and dust storms in Australia (McTainsh and Boughton, 1993; Shao, 2000). Fertile soils, consisting of clays, silts and organic matter provide soil structure and nutritive value to vegetation, but are reduced to skeletal soils by wind (McTainsh, 1989). Consequently, eroded soils are less productive and have a reduced water holding capacity (Shao, 2000).

1.2 Dust production processes

1.2.1 Components of aeolian dust processes

The production of dust-sized particles (<50 μm or <63 μm depending on the literature) has been discussed in length by researchers and a variety of mechanisms leading to their formation have been suggested (Pye, 1990). The main mechanisms proposed for fine particle production are weathering, glacial grinding, fluvial comminution and aeolian abrasion.

Entrainment, transportation and deposition are three components of aeolian dust production processes. The entrainment process represents an input into the aeolian system, transport represents a throughput within the system and deposition processes an output from the system (McTainsh, 1985). Entrained soil particles move downwind by surface creep, saltation or suspension depending on the size, shape and density of the particle. Soil particles greater than 500 μm in size are moved by surface creep (Figure 1-3). These particles rarely travel more than a few meters during an entrainment event. Saltated particles range between 100-500 μm and bounce across the land surface during an erosion event (McTainsh and Leys, 1993). These particles are too large to be suspended and rarely attain 30 cm in height from the surface. Transport distances of saltation particles range from tens to hundreds of meters during an event. On impact with other particles they can initiate movement. About 50-80 percent of total sediment transport is by saltation (McTainsh and Leys, 1993).

Particles transported in suspension are < 100 μm in diameter and may be carried to high altitudes (≤6 km) and travel over long distances (8 000 km) (McTainsh and Leys, 1993). These small "dust" particles contain important plant nutrients and their loss influences soil fertility and structure, that may in turn lead to an increase in soil erodibility at a site (Kiefert, 1995). An important consequence of both the size-selective nature of entrainment and the size-dependent mode of transport is that wind erosion changes the particle-size distribution of a soil, which can significantly affect the capacity of a soil to sustain plant growth (McTainsh and Leys, 1993). Most studies assume aeolian saltation (or dune building) processes are more important than aeolian suspension (or dust) processes in desert regions because saltation processes produce dramatic results and tangible landforms, for example sand dunes (McTainsh, 1989;

McTainsh and Leys, 1993; Livingstone and Warren, 1996; Shao, 2000). By contrast, aeolian suspension processes result in an extremely thin blanket veneering a landscape, which is easily remobilised or incorporated within an existing soil profile at a site.

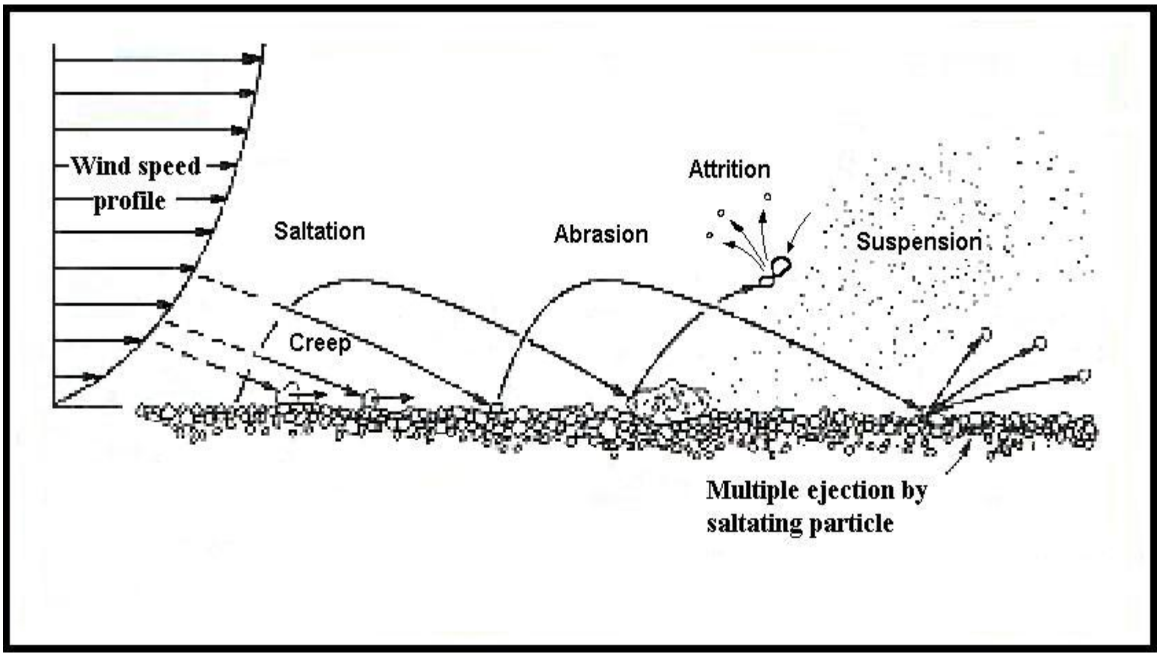


Figure 1-3: The three main modes of aeolian transport: surface creep, saltation and suspension of fine material.

(adapted from: Greeley and Iverson, 1985)

1.2.2 *Entrainment and dust production*

During a dust storm event particles are entrained from the soil surface by deflation and subsequently undergo abrasion and attrition. All three processes (Figure 1-4) provide considerable potential for the production of fine material (Figure 1-5). In the literature the terms abrasion and attrition are commonly used interchangeably. Abrasion, in particular, is often used to encompass both types of impact. Livingstone and Warren (1996) defined these terms as follows:

- entrainment: the lifting of sand into the wind.
- deflation: the net removal of material by wind.
- abrasion: the wearing down of more cohesive material by bombardment with wind-transported particles.

- attrition: the wear of clastic particles as they collide with each other in transport.

In this study, the term ‘abrasion’ is used to refer to both processes as no ready distinction could be made during experimentation.

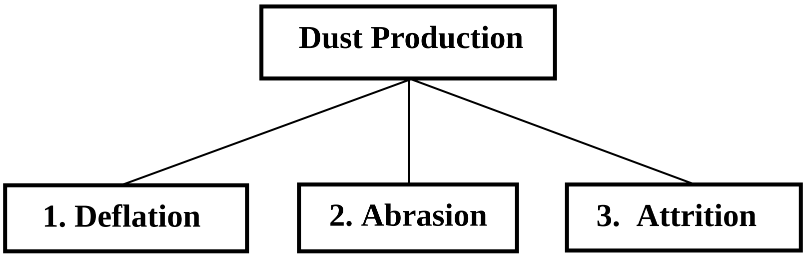


Figure 1-4: Dust production processes

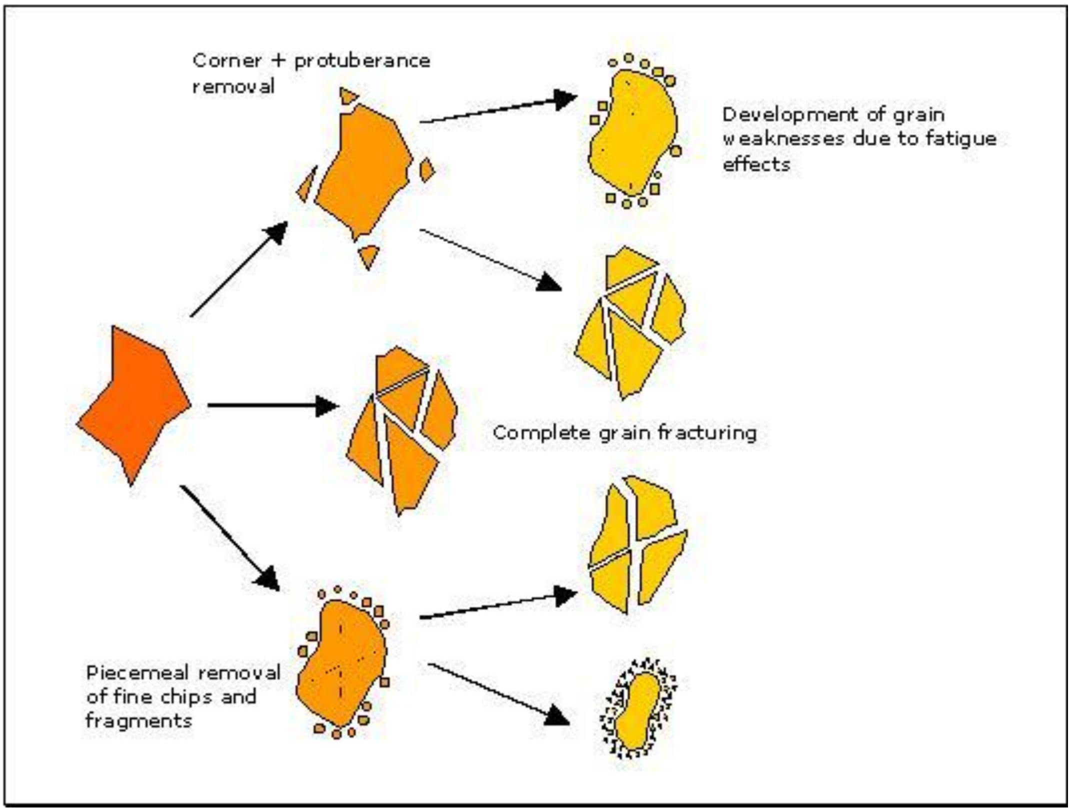
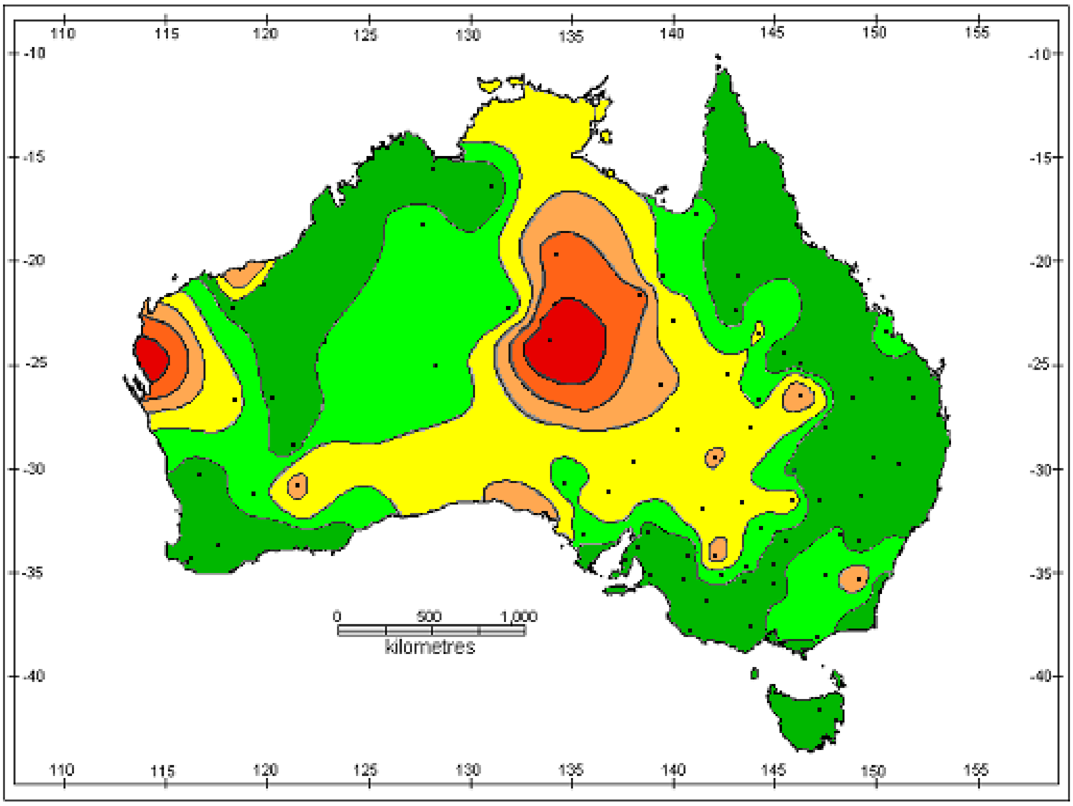


Figure 1-5: The mechanisms of fine particle production within an aeolian environment. *(Source: Wright, 1993).*

1.3 Dust production in the Simpson Desert – Channel Country

Meteorological records from the Simpson Desert-Channel Country region have shown that it has experienced an average of 23 dust storms per year for the 1960-1996 period, the highest frequency of dust storms in central Australia (McTainsh *et al.*, 1990; McTainsh *et al.*, 1999). It has been estimated that 5.5 - 6.3 million tonnes of soil was lost from a 100 000 - 200 000 km^2 area of the Simpson Desert-Channel Country region during December 1987 (Knight *et al.*, 1995) and around 15 million tonnes of dust was transported out of the region in a single event in November 1994 (McTainsh *et al.*, 1996).

Recent research has shown that most of the dust storm activity occurs in the Simpson Desert region rather than the Channel Country (McTainsh, 2003). Figure 1-6 and Figure 1-7 verify these findings. The reason for increased dust storm activity in the Simpson Desert may be attributed to the type of source material available for dust production. The Simpson Desert dunefields are aeolian quartz sands, which during dust storms are subject to abrasion processes. In contrast, fine alluvial material is the main sediment source for aeolian processes in the Channel Country. Clay skins on quartz grains are commonly found on quartz sands within the dune fields of the Simpson Desert and Channel Country (McTainsh, 2003). Dust derived from the dunes of the Simpson Desert is usually red and those of the Channel Country pale brown (Folk, 1976; Wasson, 1983; Walker, 1979; Anton and Ince, 1986; Walden and White, 1997; Kiefert, 1995; Bullard and White, 2002; McTainsh, 2003).



Legend

Dust Storm Frequency 1960-1999

🟩 0 – 50

🟩 50 – 100

🟨 100 – 200

🟧 200 – 300

🟧 300 – 400

🟥 400 - 500

Figure 1-6: Total Dust Storm Frequency across Australia 1960 to 1999

(adapted: McTainsh and Tews, 2002)

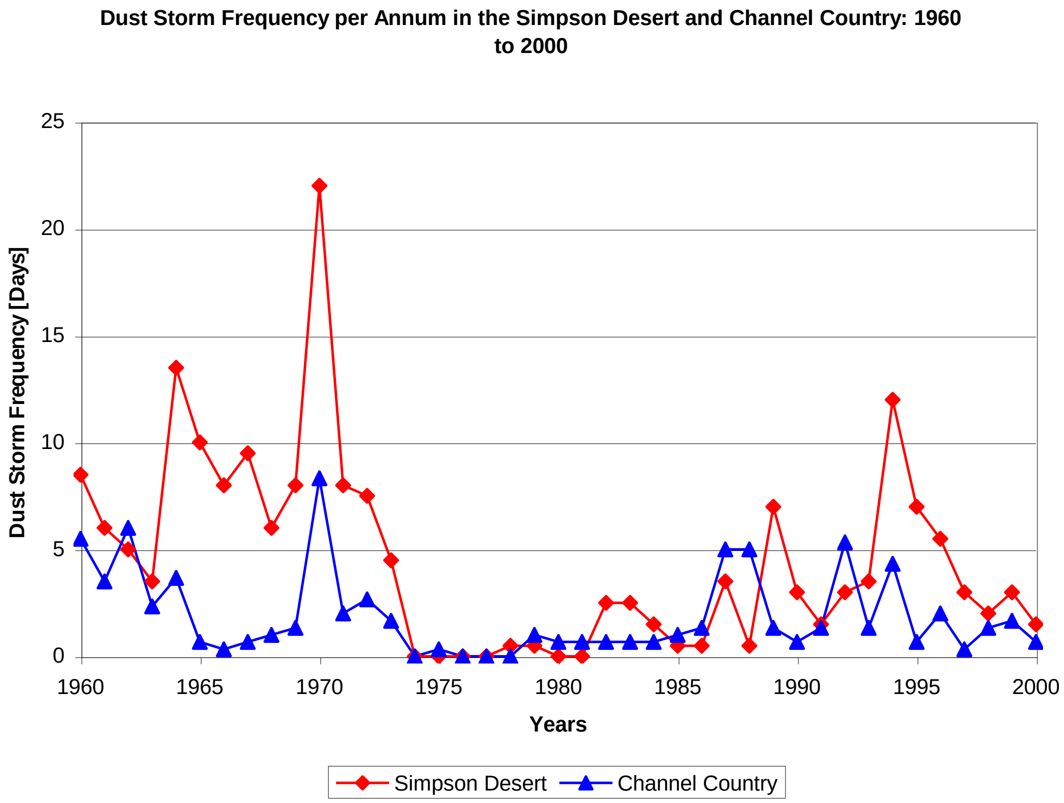


Figure 1-7: Dust storm frequency per annum in the Simpson Desert and the Channel Country.

1.4 Aims

The primary aim of this study is to investigate the potential for aeolian abrasion of natural dune sands to produce fine particles. In particular the extent to which colour, size, sorting, shape and the presence of clay skins and iron oxide coatings on grain surfaces influences the amount of dust produced. Aeolian abrasion has not been readily considered to be a potential source of dust.

1.5 Thesis Structure

This thesis presents an experimental set-up for dust production by sand grain impacts during aeolian saltation. The results may provide a better understanding of aeolian abrasion processes in nature.

Chapter 1 outlines the importance of aeolian processes on both the global and, in particular, the Australian environments. The research aims are then presented. Chapter 2 summarises previous research in the field of dust production by aeolian abrasion. The following chapter describes the study area, the field and laboratory techniques utilised and the subsequent data analysis. Chapter 4 is allocated to the presentation of results. These are then discussed in detail in Chapter 5. Chapter 6 summarises the major findings and provides recommendations for further research.

CHAPTER 2

PREVIOUS RESEARCH

2.1 Review on dust production by sand grain impact

Research into dust production by sand grain impact during aeolian saltation has focused on two main areas: the production of loess (windblown dust with a particle size between 20-50 µm) and experiments based on the abrasion of natural dune sands. Most research has been conducted within the context of the origins of loess deposits and has focused on whether the chipping and spalling of freshly-weathered (low sphericity, poorly rounded), coarse quartz grains (>250 µm) can produce particles in the 20-60 µm size range. The second field of interest is the potential for natural dune sands to produce fine material by abrasion. This area of research has not found a great deal of interest because of the assumption that chipping and spalling may be limited in natural aeolian sands and therefore the contribution of material in the loess size fraction is insignificant (Smalley and Vita-Finzi, 1968).

2.1.1 Loess experiments

Aeolian transport of sand involves both grain to soil surface impact and inter-particle collision, which together have the potential to produce considerable amounts of fine particles due to the removal of fines, particle breakage and fracture (Whalley *et al.*, 1982, 1987). The effectiveness of the aeolian abrasion process and the size characteristics of resulting fines produced are influenced by the geological history of the grains (Bullard *et al.*, 2003). The shape, size and sorting of particles from which the fines are derived influence the rate and nature of dust produced.

Experimental investigation of aeolian abrasion was first initiated by Knight (1924), Anderson (1926) and Marsland and Woodruff (1937), but Kuenen undertook the first detailed experimentation in 1960 using three different closed-circuit wind tunnels (Pye, 1990). The abrasion behaviour of cubes, crushed crystals and natural grains of limestone, feldspar and quartz was compared. Abrasion was found to increase with grain size, wind velocity, angularity and surface roughness (Gillette and Walker, 1977). Polished medium sized quartz grains and grains <50 μm in diameter were not affected by the abrasion process, but fine quartz sand grains were affected slightly (Pye, 1990). In experiments with crushed quartz, angular fragments with a diameter >50 μm and fine particles <2 μm were produced but no material was produced between 2-50 μm. However, during abrasion of crushed feldspar, medium and coarse quartz silt was produced. Consequently, Kuenen concluded that medium and coarse quartz silt found in loess cannot be of aeolian abrasion origin. In a later paper Kuenen (1969) suggested that the small amount of coarse silt produced during aeolian abrasion of quartz is due to the hardness and the nature of interparticle collisions during saltation. Krinsley and Smalley (1973) noted that quartz particles become flatter with decrease in grain size and are produced by breakage due to abrasion from larger particles.

Wright (2001) found the laboratory aeolian abrasion of freshly crushed quartz grains with very angular particle shape will initially produce more fines than sub-angular to sub-rounded natural sands (Goudie and Watson, 1991). She also found the degree of sorting in the parent material is also influential on the rate and nature of dust production. In samples with a broad particle-size range, the smaller particles are abraded to a higher degree than the coarser particles. In contrast, when samples with smaller grains are abraded, the rate of rounding is reduced whereas the abrasion of a more uniform-sized coarser sediment sample produces increased rounding. These experiments showed that angular grains initially produce high amounts of fines as corners and protuberances are removed but over time the rate of dust production decreases as grains become more rounded (Kuenen, 1960; Whalley *et al*., 1987; Wright *et al*., 1998). Previously, researchers focused on samples with a selected particle-size range for abrasion experiments. For example, Kuenen (1960) selected particles with size ranges from 400-2000 μm, Whalley *et al*., (1982) from 710-840 μm, Whalley *et al*., (1987) and Smith *et al.,* (1991) limited their size range to 350-500 μm and Wright *et al*., (1998) to 250-500 μm. The exclusion by the researchers of finer sands from the abrasion experiments may conceivably result in larger amounts of dust production than would be expected from the abrasion of a natural sand population.

2.1.2 Experiments using natural sands

Only recently has research been undertaken on the abrasion of natural dune sands with the full particle-size range (Bullard *et al.*, 2003). Most natural dunefield sediments are not clean and polished but show signs of having undergone post-depositional modification, such as having surface coatings derived from chemical precipitates (Pell *et al.*, 2000). Clay coatings are often associated with sediments from continental dune fields and are a possible source of dust (Folk, 1976; Walker, 1979; Wasson, 1983; Walden and White, 1997).

During aeolian transport coarser grains are abraded at a faster rate than finer grains and become more rounded (Walker, 1979). Consequently, the iron oxide and clay coatings on the coarser grains are removed more easily than the coatings on finer grains. Iron oxide coatings within grain pits are, however, generally protected from the abrasion process. McTainsh (1985), Shao *et al.*, (1993) and Bullard *et al.*, (2002) have shown that grains covered with iron oxide rich coatings change colour during aeolian abrasion. These results demonstrate that both iron oxide and clay coatings have the potential to act as an additional source of dust material, together with spalling, chipping and breakage, during abrasion processes. These findings resulted in the investigation if colour, size, sorting, shape and the presence of clay and iron oxide coatings on grain surfaces have the potential to influence the dust production rate as outlined in the next chapter.

CHAPTER 3

RESEARCH METHODS

3.1 Study Area

Twenty-two sand samples were collected from dune crests in central Australia. Twenty of these samples came from the Simpson Desert region and two from the Channel Country (Diamantina River area and from Windorah near Cooper Creek). The Simpson Desert is an area of dunefields extending over about 170 000 km^2 and is associated with the Lake Eyre Basin, a vast inland endoreic drainage system (Pell *et al.*, 2000). The dunefields are located where the Northern Territory, Queensland and South Australia adjoin and are bounded by the Finke and Macumba Rivers to the west, by the Mulligan and Diamantina Rivers and Eyre Creek to the east, by Lake Eyre North and the Warburton River to the south, and by an extensive sandplain to the north (Figure 3-1) (Purdie, 1984). The Simpson Desert is classified as a hot desert (Williams and Calaby, 1985) with a median annual rainfall isohyet of 150 mm. A large portion of the Simpson Desert receives less than 100 mm of rainfall per annum. Mean annual temperatures are 21-23 °C (Folk, 1971) with a maximum of 46-49 °C in Summer and a minimum of –6 °C in Winter (Purdie, 1984). Sand dunes in the Simpson Desert are longitudinal in form and have a predominantly NNW-SSE orientation, (Wasson *et al.*, 1988). These range from 10-40 m in height, to several hundred kilometres in length and the interdune space varies from 100–1500 m (Wopfner and Twidale, 1967). These dunes are also characterised by Y-junctions that commonly open to the south (Mabbutt and Sullivan, 1968). The dunes are predominantly composed of quartz sand with up to 20 percent clay pellets to the south with colours ranging from pale white to orange red to dark red (Wasson, 1983b). The primary source of sand for the modern Simpson Desert dunefields is derived from rivers and streams following episodic flooding, such as Diamantina River and Cooper and Lake Eyre Creeks. Fine alluvial sediments are eventually deposited in the Lake Eyre Basin (Twidale and Wopfner, 2001). After the flood has receded, the soil surface dries and silty sediments are deflated by the next dust storm event and transported northwards.

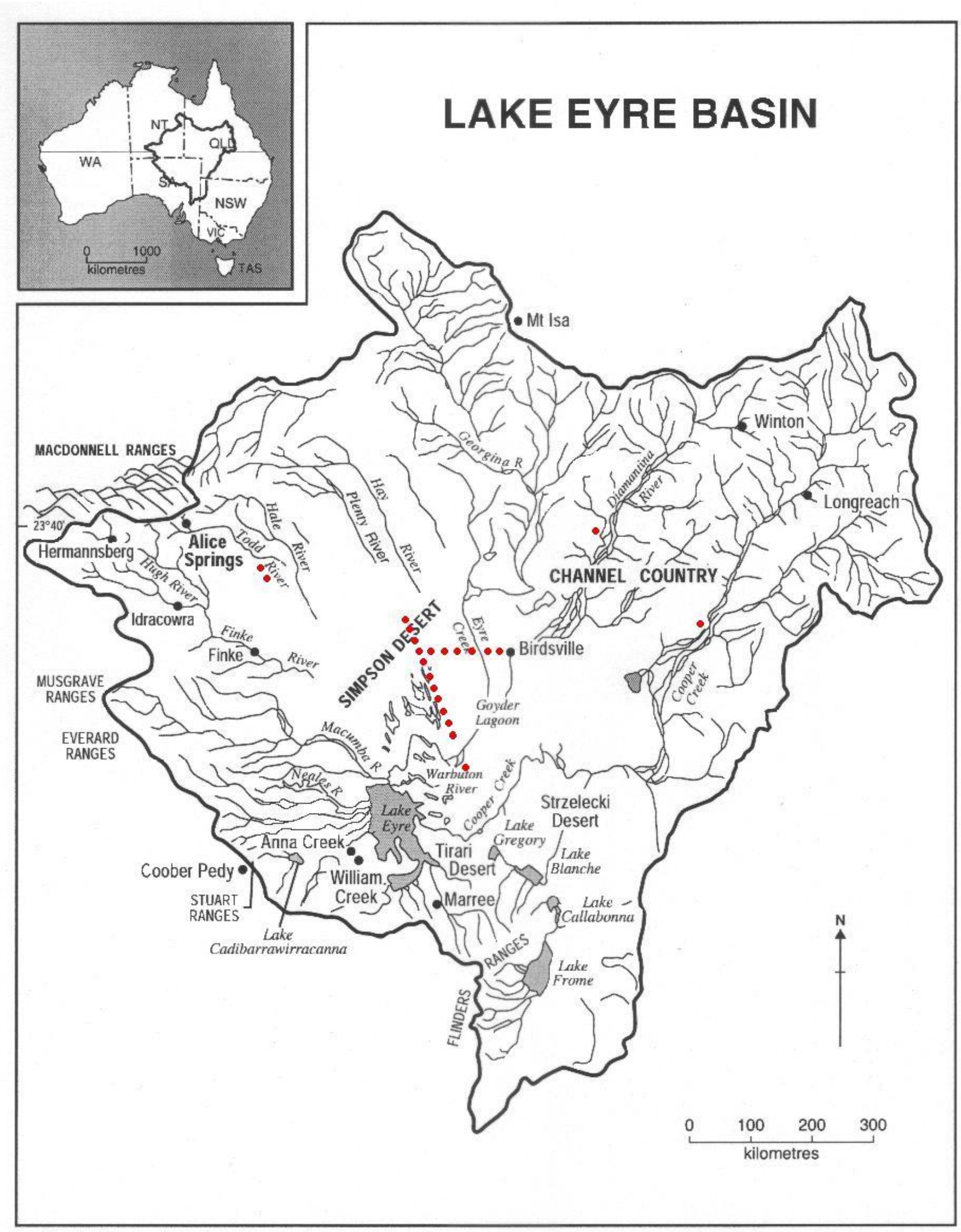


Figure 3-1: Study area with 22 sample sites (marked in red).
(adapted from: Croke et al., 1998)

3.2 Field sampling techniques

Thirty-two samples were collected from the top 0-5 cm of active, rippled dune crests in the Simpson Desert and two samples from the Queensland Channel Country. Global Positioning System (GPS) coordinates were recorded at each location. Twenty Simpson Desert samples out of the 32 were selected for this study. Eight samples (1-13) came from the southern part of the Simpson Desert, 10 sediment samples (14-28) were collected from the central part of the desert and another two (30 & 32) were taken from the northern Simpson Desert. Two samples (35 & 36) were collected from the Channel Country. The sampling locations are marked red in Figure 3-1.

3.3 Sediment colour

Soil colour provides a direct measure of soil attributes such as organic matter, iron oxide content and length and/or intensity of pedogenic processes (Kiefert, 1995). Sediments in central Australia display a range of colours from white to orange to dark red. This is attributed to the presence of iron-rich clay coatings (Wasson, 1983; Bullard & White, 2002). Clay coatings and iron oxide staining are clearly visible on quartz grain surfaces under the stereo light microscope (magnification x49). The colour of each dune sand sample was determined both before and after the abrasion experiment using the Munsell Colour Chart (1992). Munsell colours were then converted to a numerical "redness rating" using the method outlined by Torrent *et al.*, (1980):

$$\text{Redness Rating} = \frac{H \times C}{V} \quad ,$$

where H is the hue value derived from Munsell hue (a Munsell hue of 2.5YR represents a redness rating of 7.5, 5YR of 5, 7.5YR of 2.5 and 10YR of 0), C is the Munsell chroma, and V stands for the Munsell value.

3.4 Sand grain surface coatings

Mineral composition, grain roundness and sphericity, the presence of particle aggregation and the clay and iron oxide coatings of each sample were analysed using a Nikon PFX stereomicroscope. Photographs of selected dust and sand samples were taken with a digital camera mounted to a dissecting compound microscope.

The presence of iron oxide and clay coatings in dust samples were identified using a polarising petrological microscope. Scanning Electron Microscopy (SEM) was utilised to provide detailed 3-dimensional images at high magnification of selected grains. Surface textures were characterised using the classification of Krinsley and Doornkamp (1973).

3.5 Sediment roundness and sphericity

Sediment characteristics can be determined in terms of the shape of a grain. Roundness is an expression of the regularity of the margin of a grain, which abrade over time in a sedimentary environment and sphericity a measure of how well the gross geometry of a grain approaches a sphere (Pettijohn, 1957; McLane, 1995).

Fifty grains were randomly chosen, the minimum sample size required to be statistically representative, from each sample population to undertake particle roundness and sphericity measurements (Goudie *et al.*, 1991). The roundness of quartz grains was classified using the Wadell-Powers-Folk standard roundness images, with the aid of a Nikon stereo light microscope and Motic Images 2000 software tool (McLane, 1995). Although this method is subjective, it remains a common methodology for describing roundness in sedimentological studies.

Sphericity was determined using the method outlined by Zingg (1935) with a Matlab application specially written for this purpose. For the analysis it was assumed that the short axis of each grain is equal to the intermediate axis. This method was used since it is extremely difficult to determine the axes of all three sides for each grain. In addition, a petrological microscope analysis of the dust samples was performed to determine the composition of fines produced during the abrasion process.

3.6 Abrasion experiment

Aeolian abrasion experiments can be conducted in the field (Gillette and Walker, 1977; Gomes *et al.*, 1990) or in a laboratory. This research project was carried out in the laboratory as it has the advantage of controlled environmental conditions (i.e. controlled airflow, temperature and humidity) and enabled one to quantify sediment input and output, which is of particular importance since small quantities of material are to be produced. The apparatus used for the aeolian abrasion simulation experiments, a large glass ‘test-tube’ chamber, was the same design as that used by Whalley *et al.*, (1987) and Wright *et al.*, (1998) (Figure 3-2 and 3-3). The sample to be abraded is placed in the bottom of the glass chamber and agitated by a constant air stream. An electrostatic precipitator, operating at 5 kV, traps fine particles raised in suspension in the chamber. Whalley *et al.*, (1987) estimated the efficiency of this technique for trapping fine particles at 95 percent.

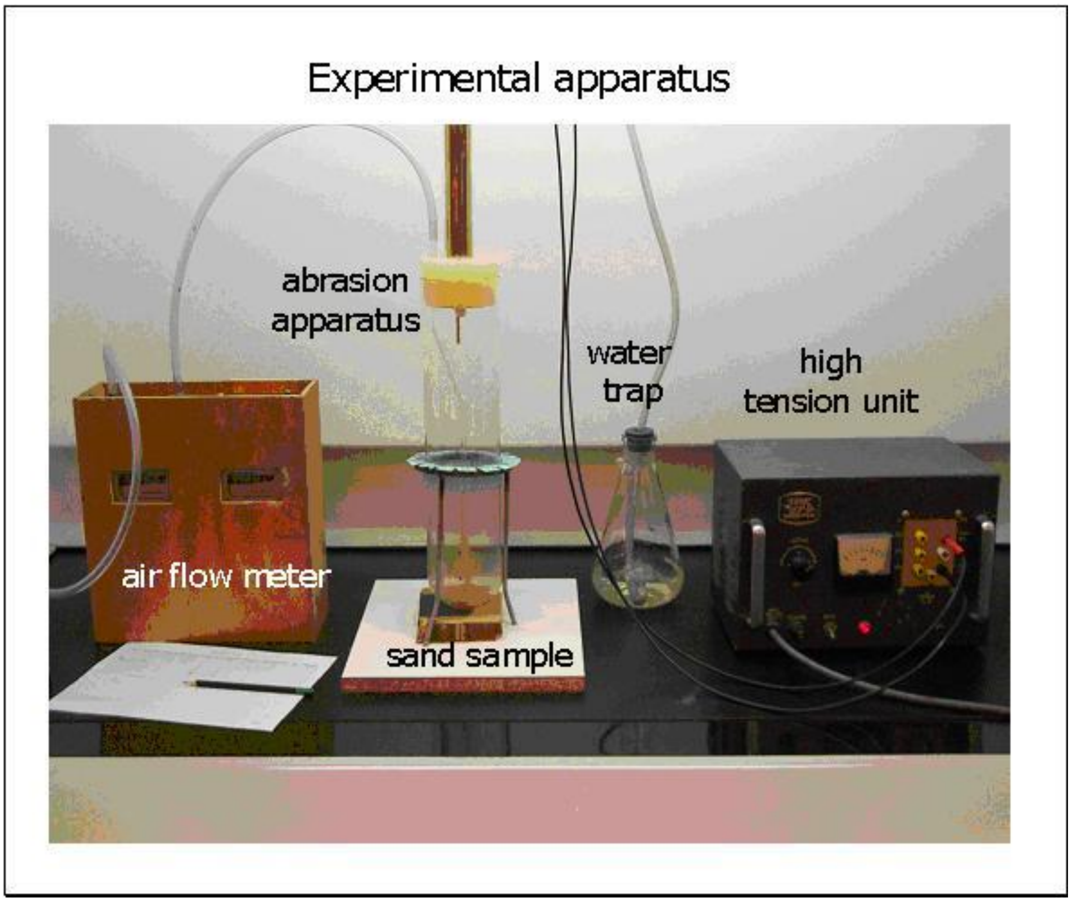


Figure 3-2: Abrasion apparatus set-up used for the abrasion experiments.

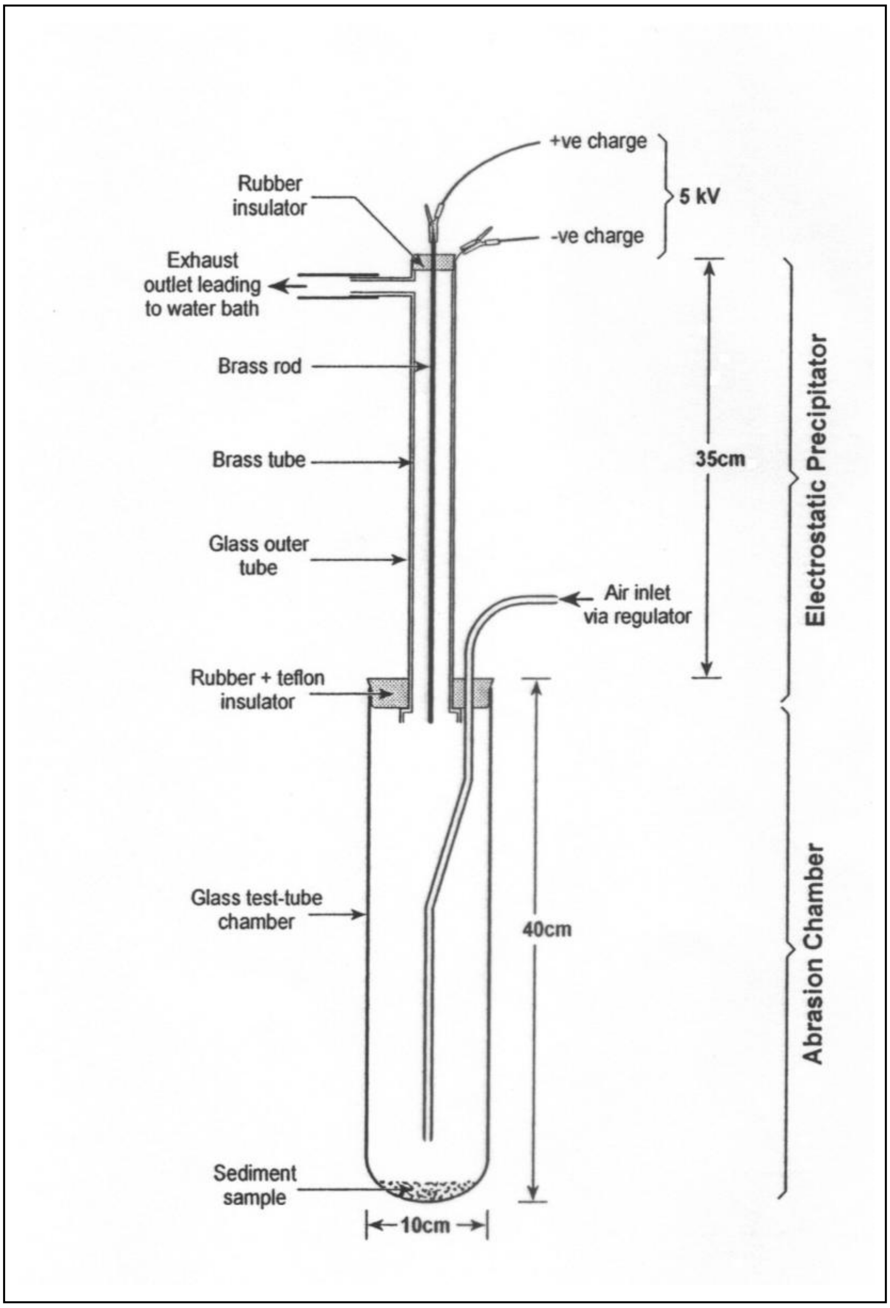


Figure 3-3: Schematic diagram of abrasion apparatus used for the experiments.

(Source: Bullard et al., 2003)

For the abrasion experiment 22 natural dune sand samples were selected. Samples were selected from a range of sediment colours, particle-sizes, degrees of sorting and shape to investigate if any of these factors influenced dust yield. For each experimental run a known quantity of dune sand (approx. 10 g) was abraded for 72 hours non-stop with a constant airflow of 0.0279 m^3/min and a velocity of 26.35 m/sec. Any fines passing the electrostatic precipitator were collected in a water bath.

During experimentation the trapping efficiency of the electrostatic precipitator was determined. At the end of each run all fines attached to the precipitator and brass rod were washed off with triple filtered deionised water. The dust solution was then filtered through a 0.45 μm nylon membrane filter. Any fines collected in the water bath were also filtered. The drying and weighing of filter papers enabled quantification of the mass of dust produced over a 72 hour abrasion period. To determine if the results obtained were reproducible samples 7, 20 and 32 were abraded three times each. Therefore, three dust samples were collected for samples 7, 20 and 32. The three weights for each sample were averaged to eliminate any biased selection of one dust weight over another.

3.7 Sediment particle-size

Particle-size is one of the fundamental properties of sediments. Geomorphic processes produce characteristic particle-size distributions during the process of entrainment, transport and deposition. Thus, particle-size analysis may provide a ‘fingerprint’ for elucidating the geomorphic processes these grains have undergone in a sedimentary environment (Livingstone and Warren, 1996).

All particle-size analyses were undertaken using a Coulter Multisizer (Figure 3-4), a precision electronic sizing instrument based on the Coulter Principle (Miller and Lines, 1988). For an analysis, particles are suspended in an electrolyte solution in a beaker and drawn through a small aperture in a glass tube (Figure 3-5). On either side of the aperture there are two electrodes submerged in the electrolyte solution, between which an electrical path of constant current is established (McTainsh *et al.*, 1997). As a particle enters the aperture a certain amount of electrolyte is displaced by the particle. This is detected by a momentary change in the electrical impedance across the aperture, which causes a small electronic pulse to occur. The number of pulses is proportional to the particle count, whereas the height of each pulse is proportional to the volume of the particle (Miller and Lines, 1988). The series of pulses is then electronically scaled, counted and accumulated in a number of size-related channels, which is displayed as a particle-size distribution curve. This particle-sizing technique produces very high-resolution analysis (up to 256 size classes per sample) with an analytical size range from 0.4-600 μm (McTainsh *et al.*, 1997).

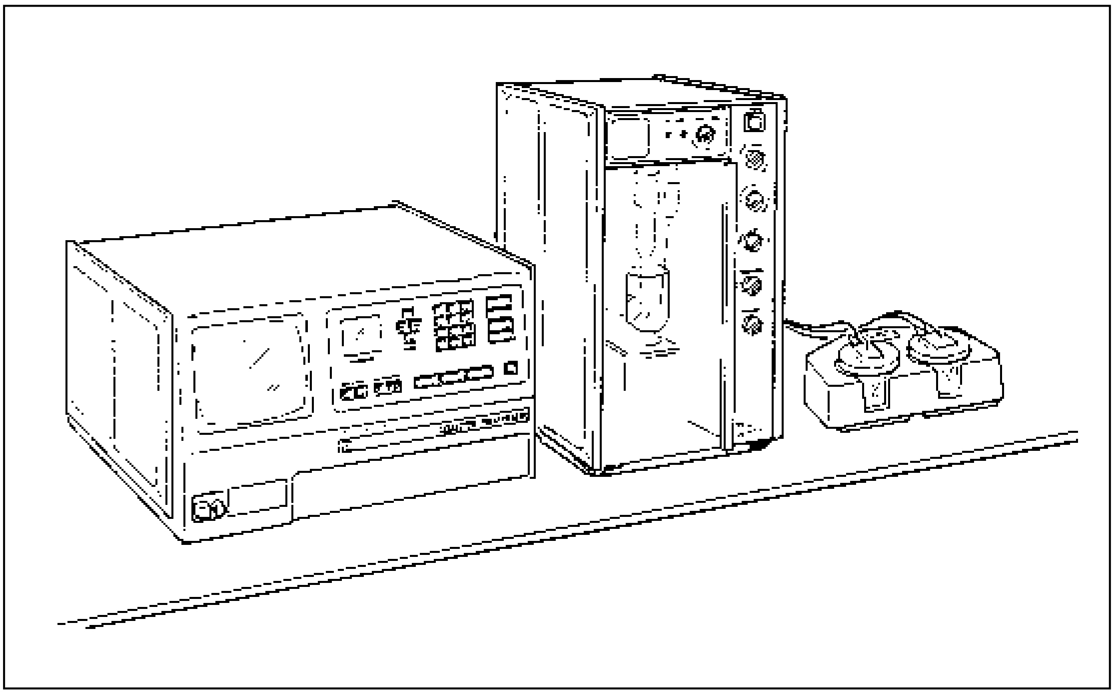


Figure 3-4: The Coulter MULTISIZER

(Source: Coulter Electronics Limited, 1988)

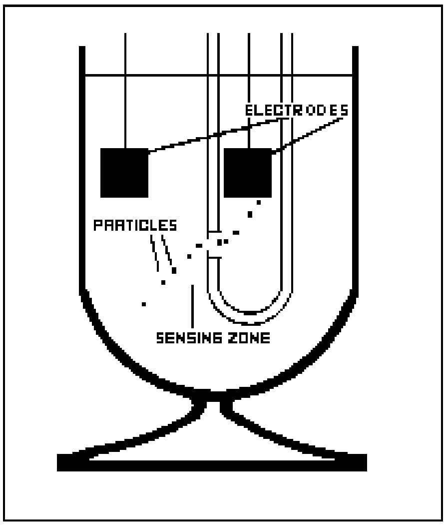


Figure 3-5: The Coulter Principle

Schematic illustration of a sample beaker with electrodes and orifice tube for particle-size analysis. (*Source:* Coulter Electronics Limited, 1988)

3.8 Statistical analysis

Statistical analyses were conducted using data from: particle-size, sorting, colour, roundness, sphericity and dust production rate. Each of these five variables components was linked to dust production for the 22 samples studied. A linear regression analysis is used to investigate the influence of the independent variables (particle-size, sorting, colour, roundness, sphericity) on the dependent variable (dust).

A stepwise multiple regression analysis using SAS, a statistical analysis program, was utilised to determine which set of independent variables have the greatest influence on the rate of dust production. The advantage of using multiple regression models is that it is possible to establish which set of independent variables explain a proportion of the variance in a dependent variable (dust) at a significant level (R^2). These can then be used to establish the relative predictive importance of the independent variable.

CHAPTER 4

RESULTS

4.1 Introduction

This chapter summarises the results obtained from the abrasion study. These include the findings from the colour analyses of the dune samples both before and after abrasion as well as the colour determinations of dust produced. Following these are the results of the sand grain surface coatings and sediment characteristics analyses, the data obtained from the abrasion experiments and particle-size analyses. Statistical analysis using SAS and Matlab software programs provide an essential tool to determine the individual influence mean particle-size, sorting, colour, roundness and sphericity have on the dust produced.

4.2 Sediment colour

The colour variation of sand samples is attributed to the presence of clay coatings and iron oxide pigments. Clay coatings display a range of colours but the iron-rich nature of the coatings on the surface of the sand grains gives these the red colour. Redness ratings for sediments range from yellow (0) to dark brown (3) to red (15) (Torrent *et al*., 1980). For the majority of samples the colour of sand grains becomes lighter after 72 hour abrasion (Table 4-1). The colour change is particular evident in samples 13, 14, 20, 25, 26, 27, 30, 32 and 36 (Figure 4-1).

Linear regression analysis of colour versus dust production yields an R^2 of 0.0595 (Figure 4-2). Figure 4-3 displays the colour of all dust sample collected.

Table 4-1: Colour of initial dune sand sample, abraded sample and dust.

Sample ID	Munsell Colour before abrasion	Colour before abrasion	Redness† Rating before abrasion	Munsell Colour after 72 hrs abrasion	Redness† Rating after 72 hrs abrasion	Redness† Rating of Dust
1	10YR 7/4	very pale brown	0	10YR 7/3	0	0
2	10YR 7/4	very pale brown	0	10YR 7/3	0	0
3	10YR 7/4	very pale brown	0	10YR 7/3	0	0
6	7.5YR 6/8	reddish yellow	3	7.5YR 7/6	2	0
7	10YR 7/6	yellow	0	10YR 7/4	0	0
9	7.5YR 7/6	brownish yellow	2	10YR 6/6	0	0
10	7.5YR 6/8	reddish yellow	3	7.5YR 6/6	3	2
13	5YR 6/8	reddish yellow	7	7.5YR 6/8	3	2
14	5YR 6/8	reddish yellow	7	7.5YR 6/8	3	2
18	5YR 5/8	yellowish red	8	5 YR 5/8	8	2
19	5YR 5/8	yellowish red	8	5 YR 5/8	8	2
20	2.5YR 5/8	reddish yellow	12	5YR 5/8	8	4
21	5YR 5/8	yellowish red	8	5 YR 5/8	8	2
23	5YR 5/8	yellowish red	8	5 YR 5/8	8	2
25	5YR 7/8	reddish yellow	6	7.5YR 6/6	3	2
26	5YR 6/8	reddish yellow	7	7.5YR 5/8	4	2
27	5YR 6/6	reddish yellow	5	7.5YR 6/6	3	1
28	7.5YR 6/6	reddish yellow	3	7.5YR 6/6	3	0
30	2.5YR 4/8	red	15	5YR 5/8	8	5
32	5YR 5/8	yellowish red	8	5YR 5/6	6	3
35	7.5YR 5/6	strong brown	3	7.5YR 5/6	3	2
36	2.5YR 5/8	reddish yellow	12	5YR 5/6	8	7

†Torrent *et al.*, (1980)

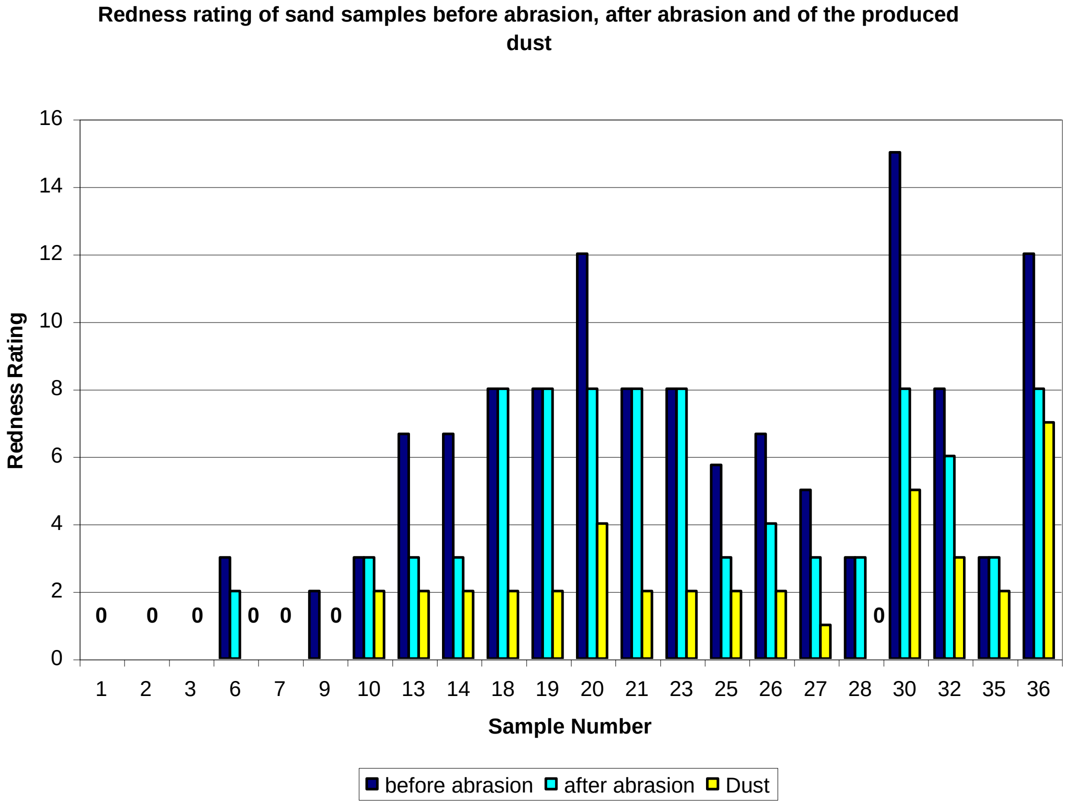


Figure 4-1: Redness rating of sand samples before abrasion, after abrasion and of produced dust.

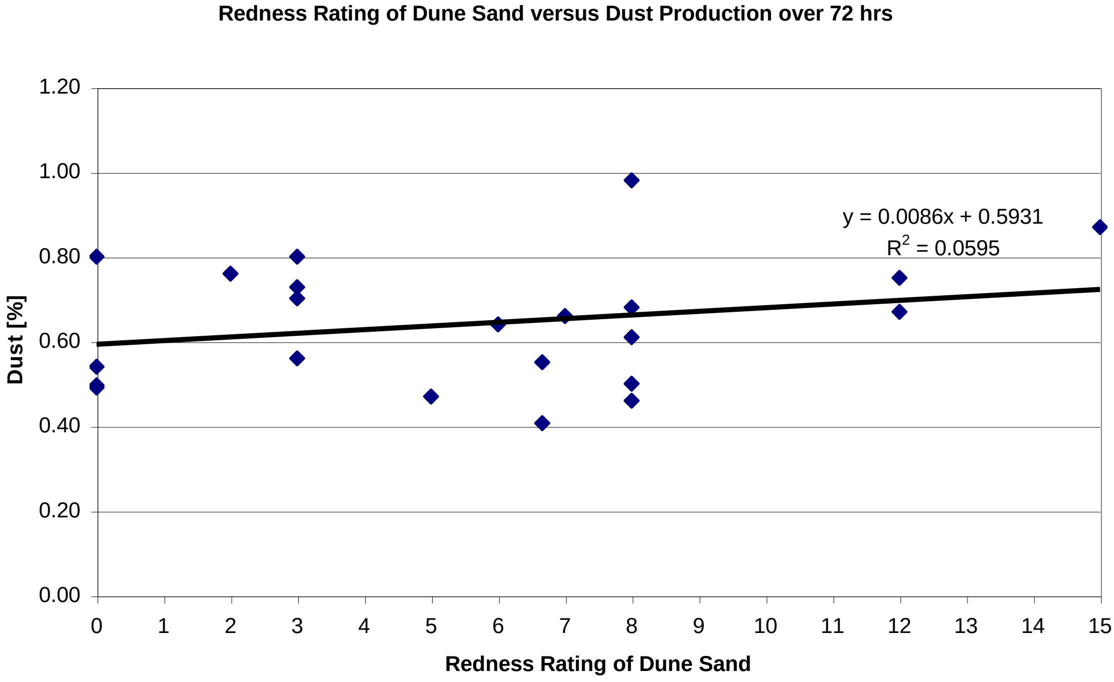


Figure 4-2: Redness rating of dune sand versus dust production over 72 hrs.

Figure 4-3: Colour of dust samples collected.

4.3 Sand grain surface coatings

Microscopic analysis of natural dune sand samples reveal the presence of clay coatings and iron oxide pigments on the surfaces of clear and frosted quartz grains.

Photographs taken from a selected range of sand samples display variation in grain colour and shape (Figures 4-4 to 4-6). All microscopic examination was undertaken at x49 magnified.

The sand sample in Figure 4-4 displays clear to frosted quartz grains. Limited iron oxide staining is visible.

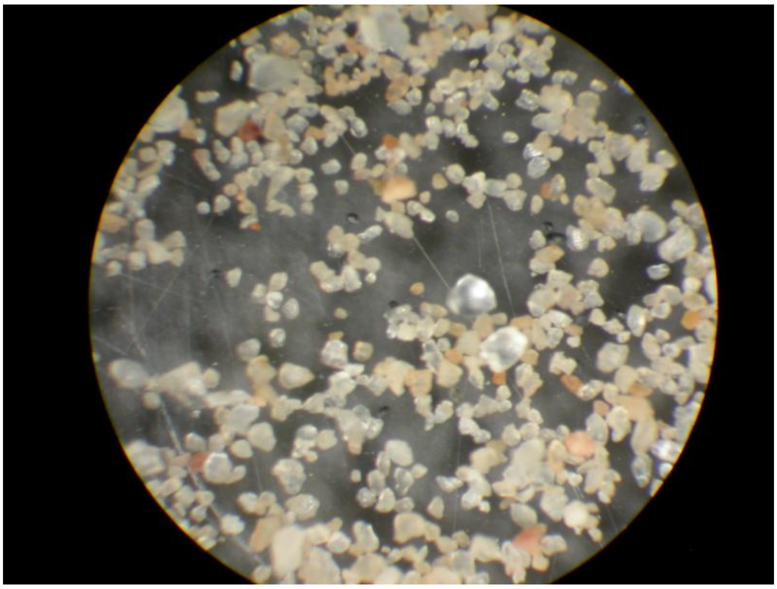


Figure 4-4: Simpson Desert Sample 7.

Most sand grains in Figure 4-5 are covered with haematite stained clay coatings.

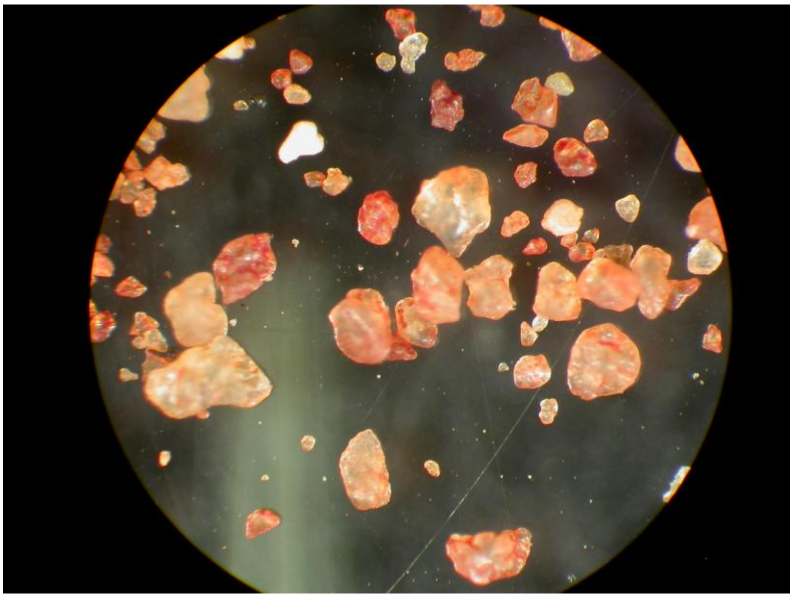


Figure 4-5: Simpson Desert Sample 32.

The sand grains from the Windorah region display a red coating, which is related to the presence of haematite.

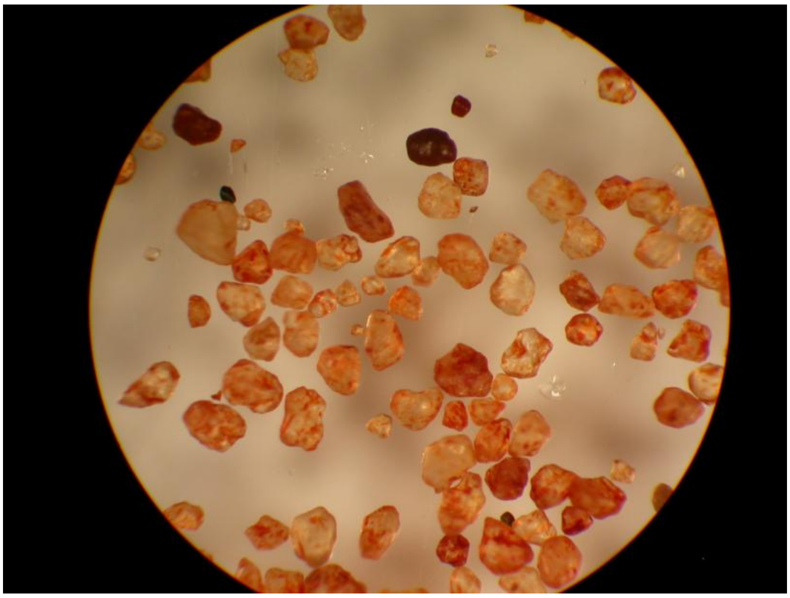


Figure 4-6: Sample 36, Windorah, Channel Country.

Figures 4-7 and 4-8 show dust material produced after 72 hours abrasion. The larger particles are quartz fragments, which have been generated by chipping, spalling or breakage of larger grains during the abrasion process. The abraded dust from sand sample 7 has the same colour as the parent material (Figure 4-7).

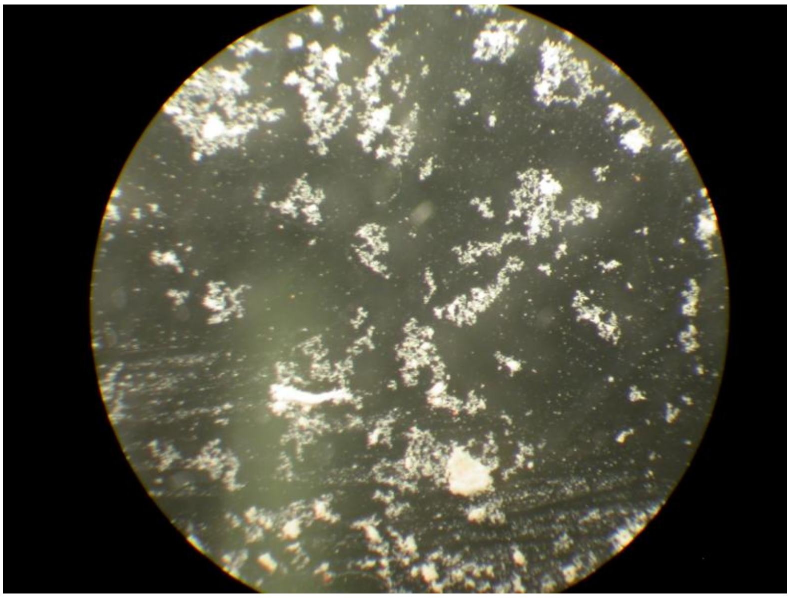


Figure 4-7: Dust material from Simpson Desert, Sample 7.

The abraded dust collected from sample 32 appears lighter in colour than the parent material.

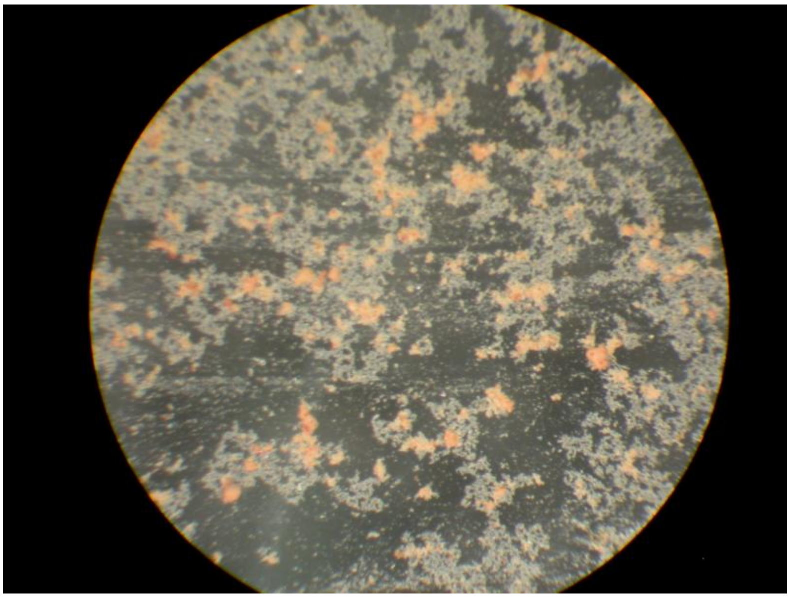


Figure 4-8: Dust material from Simpson Desert, Sample 32.

Petrological microscopic examination verified that clay and iron oxide coatings are present in the dust material produced during abrasion. Under crossed polarised light, clay coatings exhibit birefringence colours whereas iron oxide pigments appear opaque.

Figure 4-9 shows a Scanning Electron Microscope image (magnification x100) of a sand grain from the Diamantina area, sample 35. The sands from this region are covered with red clay skins and iron oxide pigments. The electromicrograph shows a rounded quartz grain (500 µm) exhibiting conchoidal breakage surfaces. An adhesion is highlighted in the centre of the grain.

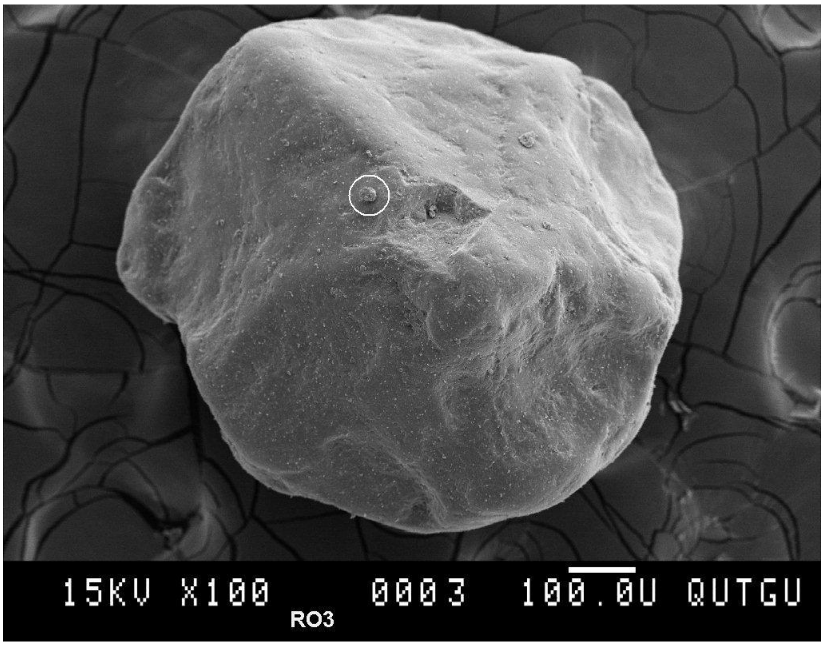


Figure 4-9: SEM of quartz grain from Diamantina, Channel Country.
Scale bar=100 µm.

The electromicrograph in Figure 4-10 shows a higher resolution image (magnification x3000) of an adhesion, encircled in the centre of Figure 4-9. The adhesion is approximately 20 µm in diameter. During aeolian abrasion this particle is easily removed from the surface of the larger grain and carried in suspension. Upturned plates are also visible.

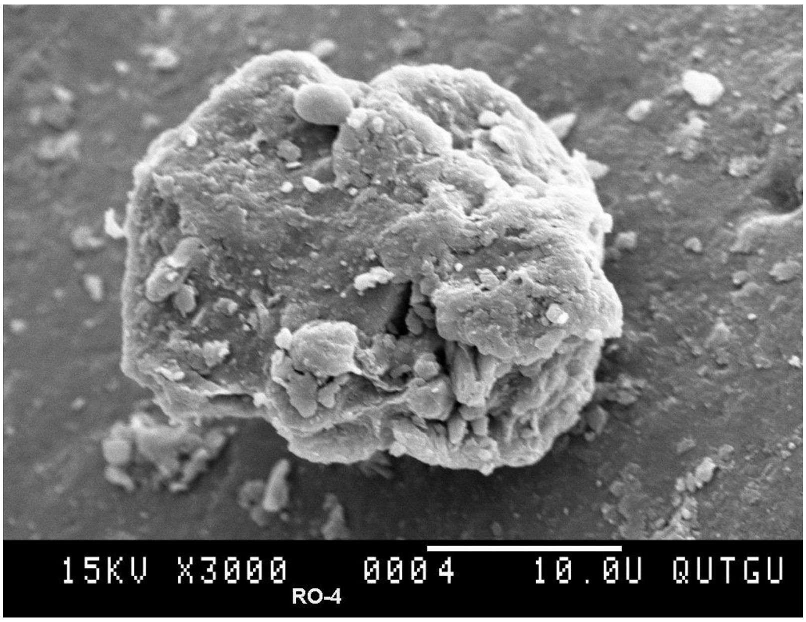


Figure 4-10: SEM close-up of particle from the centre of Figure 4-9.
Scale bar=10 µm.

4.4 Sediment roundness and sphericity

Roundness (ρ) values may range from 0 = very angular to 6 = well rounded. Table 4-2 shows the ρ values for the 22 samples range from 3.10 (sub-angular) to 4.20 (sub-rounded

Table 4-2: Mean roundness and sphericity values.

Sample ID	Roundness	Roundness [ρ scale] [†]	Sphericity‡	Dust Yield [%]
1	sub-rounded/sub-angular	3.66	0.71	0.54
2	sub-rounded	3.84	0.75	0.49
3	sub-rounded	3.78	0.73	0.50
6	sub-rounded	3.82	0.73	0.70
7	sub-rounded/sub-angular	3.58	0.73	0.80
9	sub-rounded	4.06	0.74	0.76
10	sub-rounded	3.86	0.73	0.73
13	sub-angular/sub-rounded	3.48	0.75	0.55
14	sub-angular/sub-rounded	3.28	0.76	0.41
18	sub-rounded/sub-angular	3.68	0.71	0.68
19	sub-rounded	3.80	0.75	0.50
20	sub-rounded	3.82	0.73	0.67
21	sub-rounded/sub-angular	3.70	0.73	0.61
23	sub-rounded/sub-angular	3.74	0.72	0.46
25	sub-angular/sub-rounded	3.50	0.70	0.64
26	sub-rounded/sub-angular	3.58	0.75	0.66
27	sub-rounded/sub-angular	3.57	0.75	0.47
28	sub-rounded	3.76	0.77	0.56
30	sub-rounded	3.96	0.73	0.87
32	sub-rounded	3.90	0.72	0.98
35	sub-angular	3.10	0.77	0.80
36	sub-rounded	4.20	0.78	0.75

[†] Wadell-Powers-Folk standard roundness images (McLane, 1995)

‡Zingg (1935) values: > 0.67 more spherical; <0.67 less spherical

Sphericity values may range from > 0 = acicular to 1 = spheroidal. The overall sphericity of all samples varied only slightly and ranged from 0.70 to 0.78 (more spherical) (Table 4-2). Linear regression analysis using roundness and sphericity data show the R^2 values are 0.0845 and 0.0168 respectively (Figures 4-11 and 4-12).

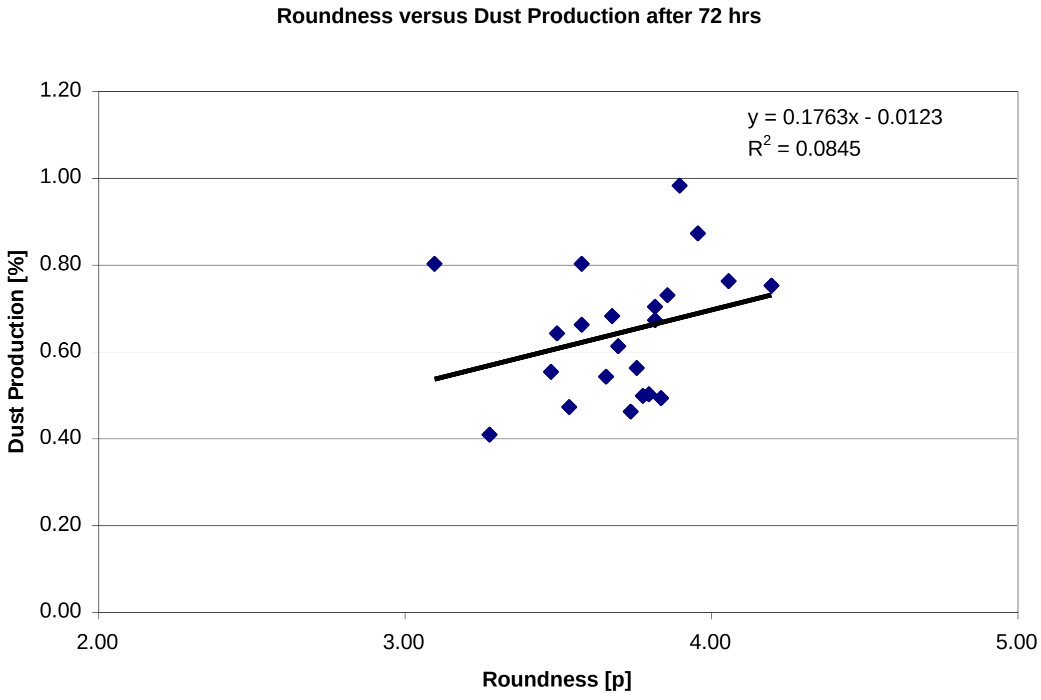


Figure 4-11: Roundness versus dust production after 72 hrs.

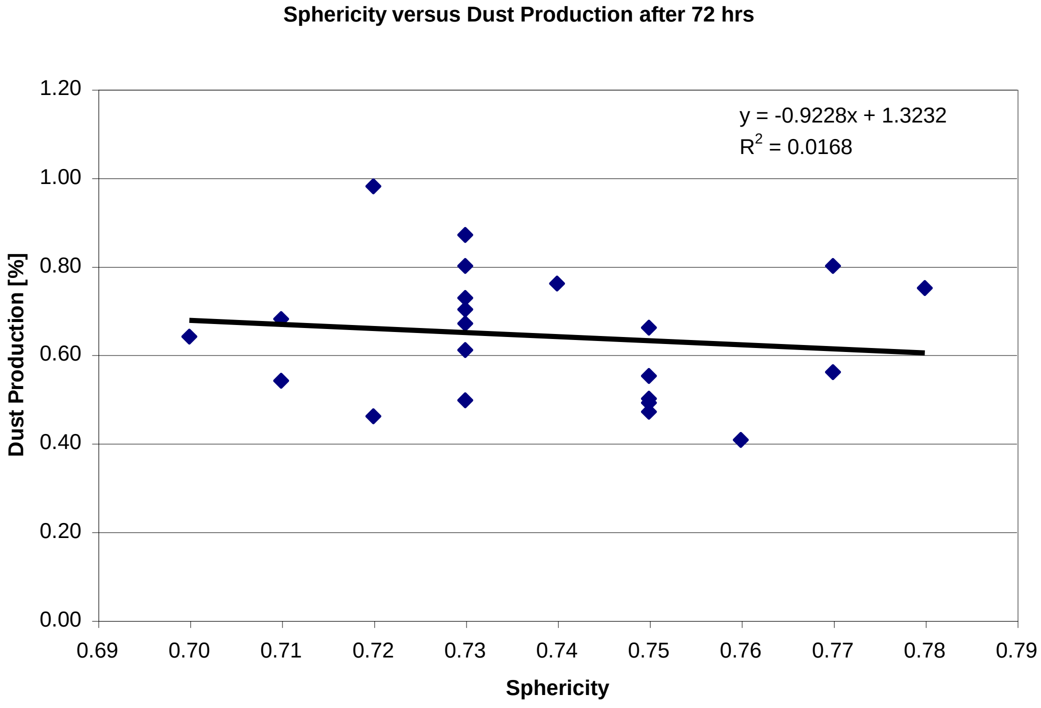


Figure 4-12: Sphericity versus dust production after 72 hrs.

Figure 4-13 displays the location of all 22 samples in relation to roundness versus sphericity.

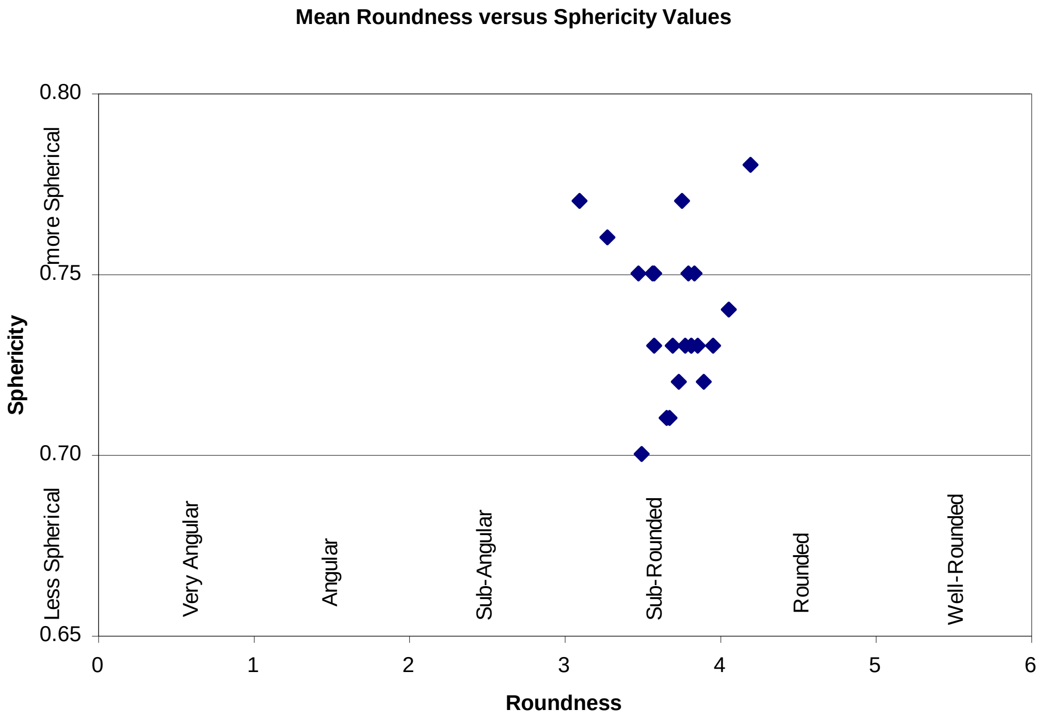


Figure 4-13: Mean roundness versus sphericity values.

4.5 Abrasion experiment

During the abrasion process grains collide with each other in the abrasion chamber. The resulting collisions produce fine material by either chipping or spalling of sand grains as well as the removal of coatings from the surface of quartz grains. Table 4-3 shows that 0.41-0.98% of the initial sand sample weight was abraded and collected as dust over a 72 hour time period.

The dust trapping efficiency of the electrostatic precipitator averaged 60 percent after the 72 hour abrasion period. This compared to a 95 percent trapping efficiency obtained by Whalley *et al.*, (1987) after 24 hour of abrasion. The remaining 40 percent of dust was collected in the water bath. However, this dust was included in the overall dust production weight for each sample.

Table 4-3: Dust production after 72 hours of abrasion.

Sample ID	Initial sample weight of dune sand sample [g]	Dust produced after 72 hr abrasion [g]	Total dust yielded of initial sample weight [%]
1	10.5148	0.0568	0.54
2	10.0028	0.0491	0.49
3	10.0349	0.0498	0.50
6	10.4380	0.0732	0.70
7	10.6509	0.0852	0.80
9	10.4219	0.0850	0.76
10	10.6505	0.0777	0.73
13	12.0324	0.0663	0.55
14	12.1915	0.0499	0.41
18	10.1197	0.0687	0.68
19	10.7013	0.0535	0.50
20	10.1439	0.0677	0.67
21	9.5530	0.0582	0.61
23	11.0239	0.0509	0.46
25	10.1000	0.0644	0.64
26	10.4534	0.0692	0.66
27	10.5783	0.0498	0.47
28	10.3879	0.0584	0.56
30	10.3232	0.0901	0.87
32	10.0924	0.0988	0.98
35	10.7914	0.0860	0.80
36	10.0849	0.0423	0.75

4.6 Sediment particle-size

Particle-size analysis was conducted on all 22 sand samples prior to abrasion using a Coulter Multisizer. These analyses (see Table 4-4) provide information about the particle-size distribution, mean particle-sizes, modes present and the standard deviation. Mean particle-sizes range from 141.3-309.5 µm, modes from 140.1-358.0 µm and standard deviations from 37.9-145.0 µm. The degree of sorting (Table 4-4) was calculated using the method outlined by Folk and Ward (1957).

Table 4-4: Mean size and standard deviation of the 22 samples.

Sample ID	Mean [µm]	Mode [µm]	Standard Deviation [µm]	Degree of Sorting †	Dust Yield [%]
1	180.0	186.3	43.8	well sorted	0.54
2	187.0	186.3	40.6	very well sorted	0.49
3	141.8	148.9	39.9	well sorted	0.50
6	152.9	174.4	45.8	well sorted	0.70
7	194.6	190.2	115.0	moderately well sorted	0.80
9	240.8	195.4	109.0	moderately well sorted	0.76
10	165.7	169.7	46.4	well sorted	0.73
13	188.8	183.9	52.8	well sorted	0.55
14	141.3	146.1	37.9	well sorted	0.41
18	166.6	176.8	54.1	well sorted	0.68
19	142.8	140.1	50.8	well sorted	0.50
20	159.9	172.8	53.9	well sorted	0.67
21	231.5	274.2	104.0	moderately well sorted	0.61
23	211.7	184.6	59.7	well sorted	0.46
25	179.6	183.1	46.9	well sorted	0.64
26	172.0	179.3	56.2	well sorted	0.66
27	228.8	227.9	75.7	well sorted	0.47
28	198.1	204.7	49.9	well sorted	0.56
30	309.5	358.0	105.0	moderately well sorted	0.87
32	262.8	237.6	124.0	moderately well sorted	0.98
35	248.7	175.6	145.0	moderately sorted	0.80
36	232.8	265.2	53.8	very well sorted	0.75

† Folk and Ward (1957)

Linear regression analysis displays that 34 percent of variation in dust production is explained by the mean particle-size (Figure 4-14).

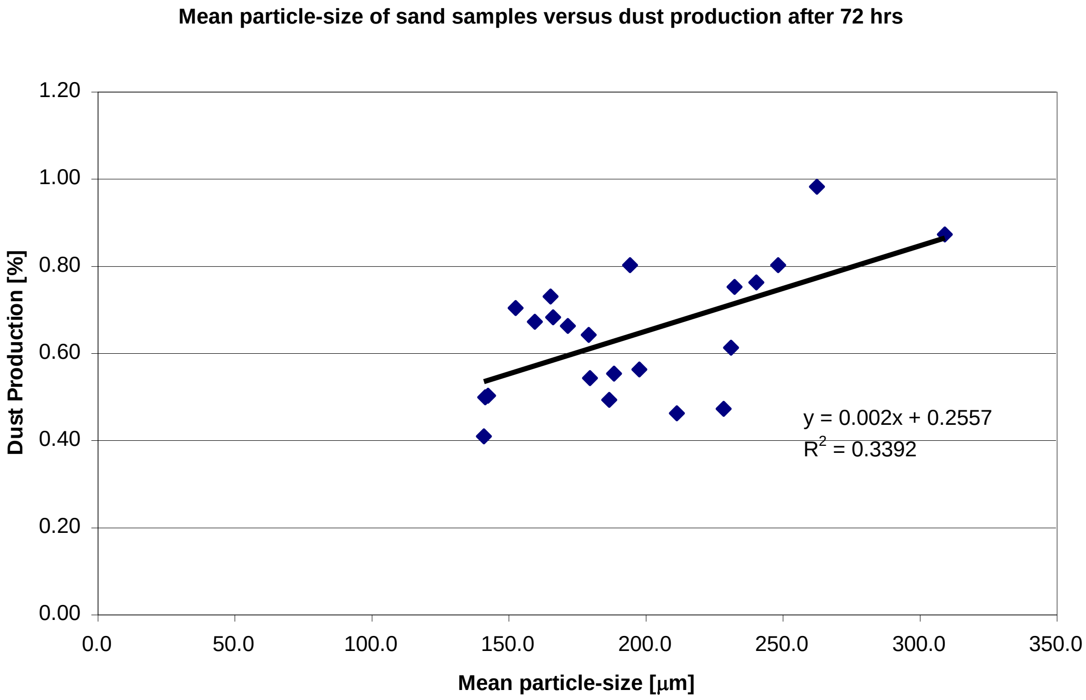


Figure 4-14: Mean particle-size of sand samples versus dust production after 72 hrs.

Another aspect to be considered is the influence the degree of sorting (standard deviation) has on the rate of dust production. Linear regression analysis (Figure 4-15) shows 46 percent of variation in dust yield is due to the variation in the degree of sorting ($R^2 = 0.4597$).

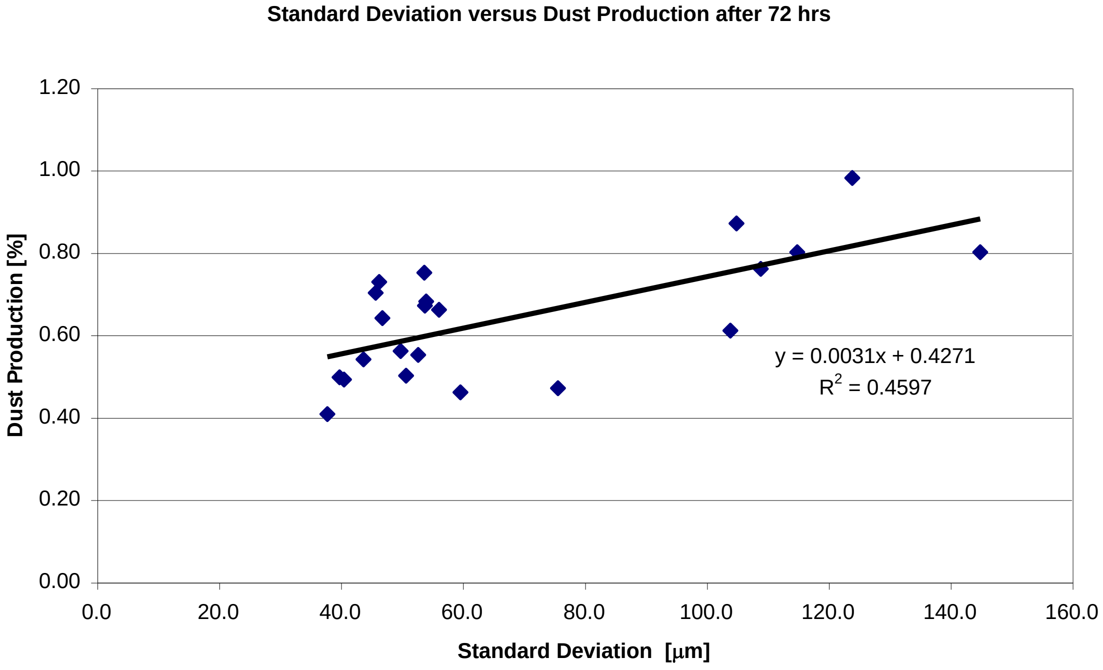


Figure 4-15: Standard deviation versus dust production over 72 hrs.

Linear regression analysis of standard deviation versus mean particle-size shows two distinctive populations (Figure 4-16). In the first population 73 percent of samples (16 out of 22) have a mean particle-size range between 141.3-232.8 μm and a standard deviation between 37.9 to 75.7 μm. These are very well to well sorted fine sands. The remaining 6 samples (27 percent) are moderately well to moderately sorted (standard deviation between 104.0-145.0 μm) with a mean particle-size ranging between 240.8-309.5 μm. The R^2 value of 0.5716 indicates that 57 percent of the variations in mean particle-size is explained by standard deviation. These results suggest that as the mean particle-size of the dune sand samples increases, the degree of sorting decreases.

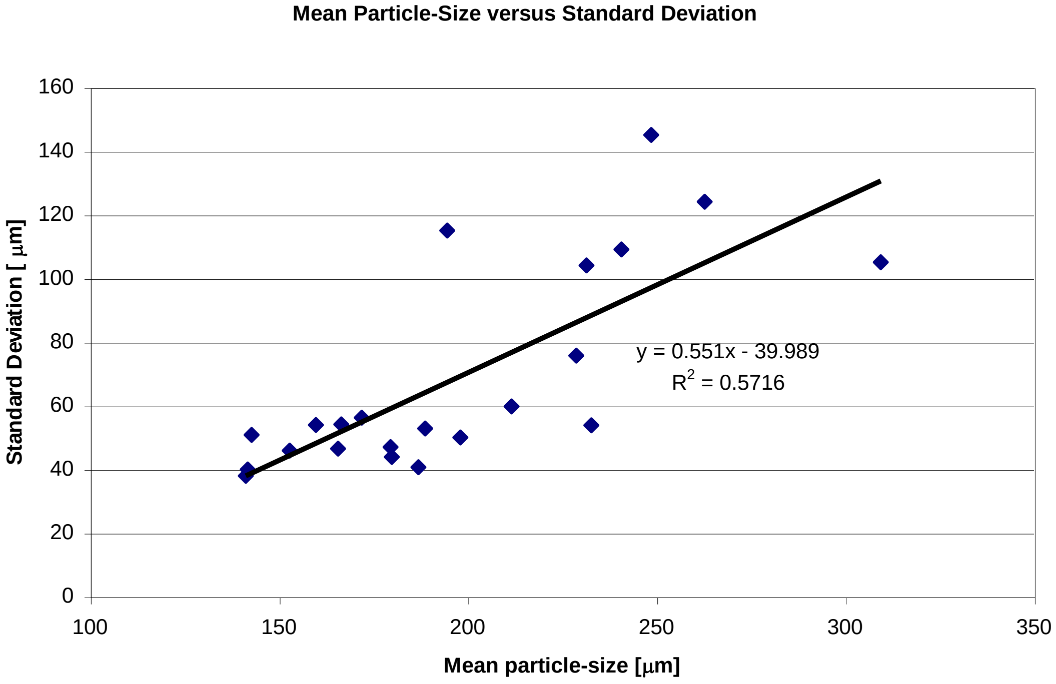


Figure 4-16: **Standard Deviation versus Mean Particle-size.**

The particle-size distributions (PSD) of all 22 samples have been grouped according to their degree of sorting and mean particle-size and are shown in Figures 4-17 to 4-21. Individual PSD's are in Appendix 1, labelled (a) to (v). The group displayed in Figure 4-16 are very well to well sorted dune sand samples with a mean particle-size ranging from 180-198 µm.

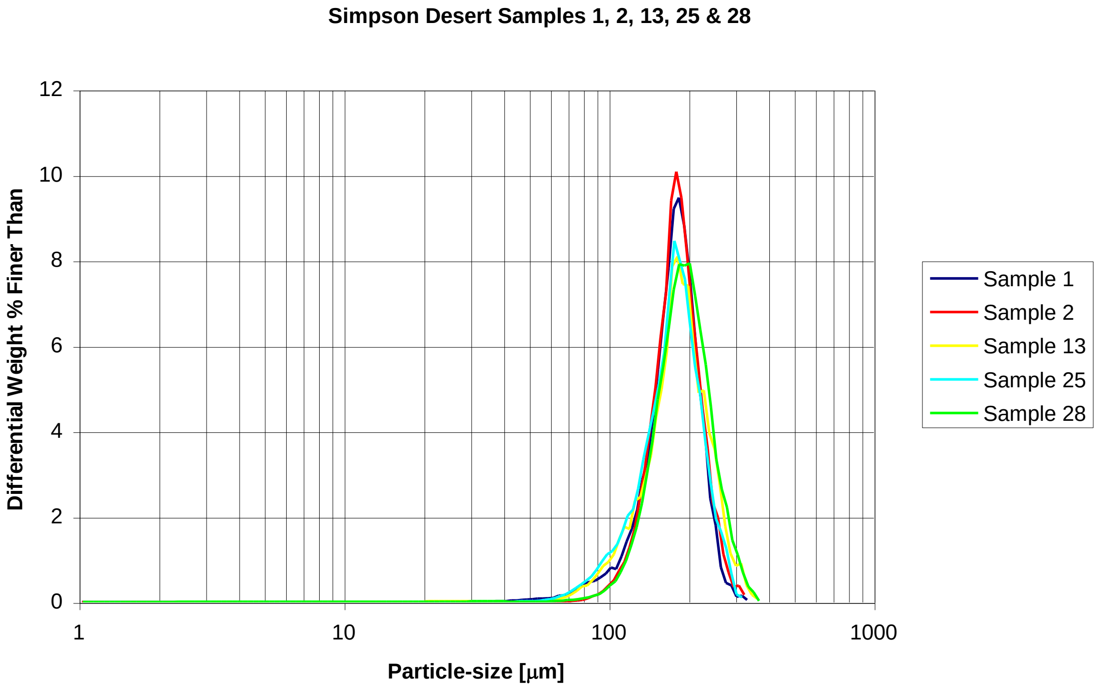


Figure 4-17: PSD's of Samples 1, 2, 13, 25 and 28.

R48 represents Simpson Desert Sample 1
R68 represents Simpson Desert Sample 2
R106 represents Simpson Desert Sample 13
R109 represents Simpson Desert Sample 25
R111 represents Simpson Desert Sample 28

Samples 3 and 14 are well sorted and very fine dune sands with a mean particle-size of 141 µm (Figure 4-18).

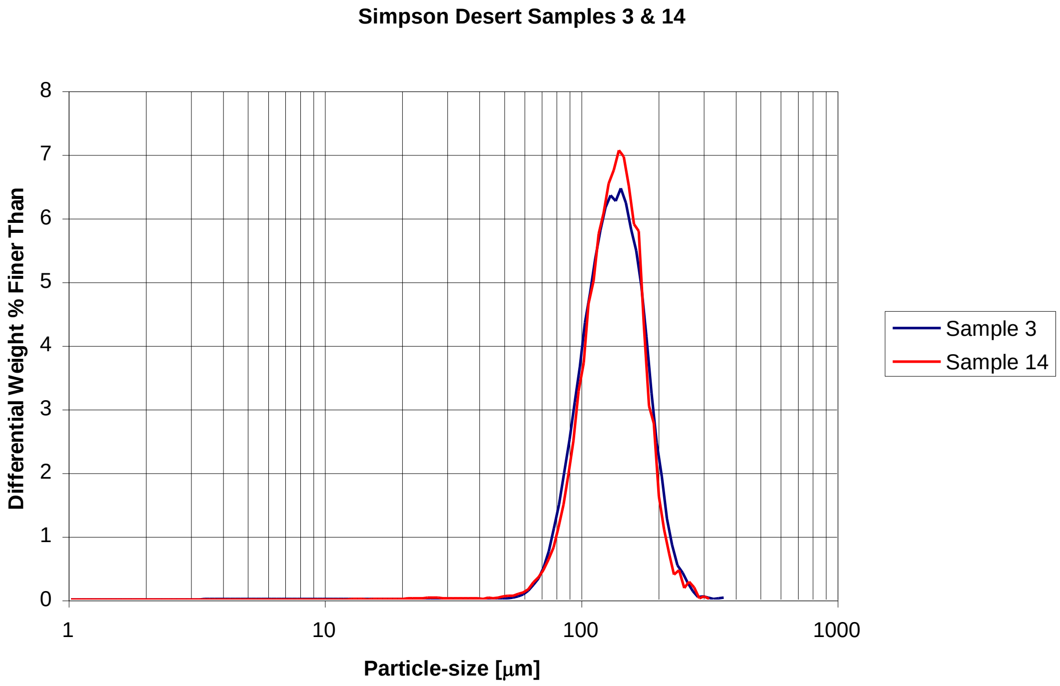


Figure 4-18: PSD's of Samples 3 and 14.

R69 represents Simpson Desert Sample 3
R50 represents Simpson Desert Sample 14

The sand samples in Figure 4-19 are well sorted with a mean particle-size between 153-172 µm.

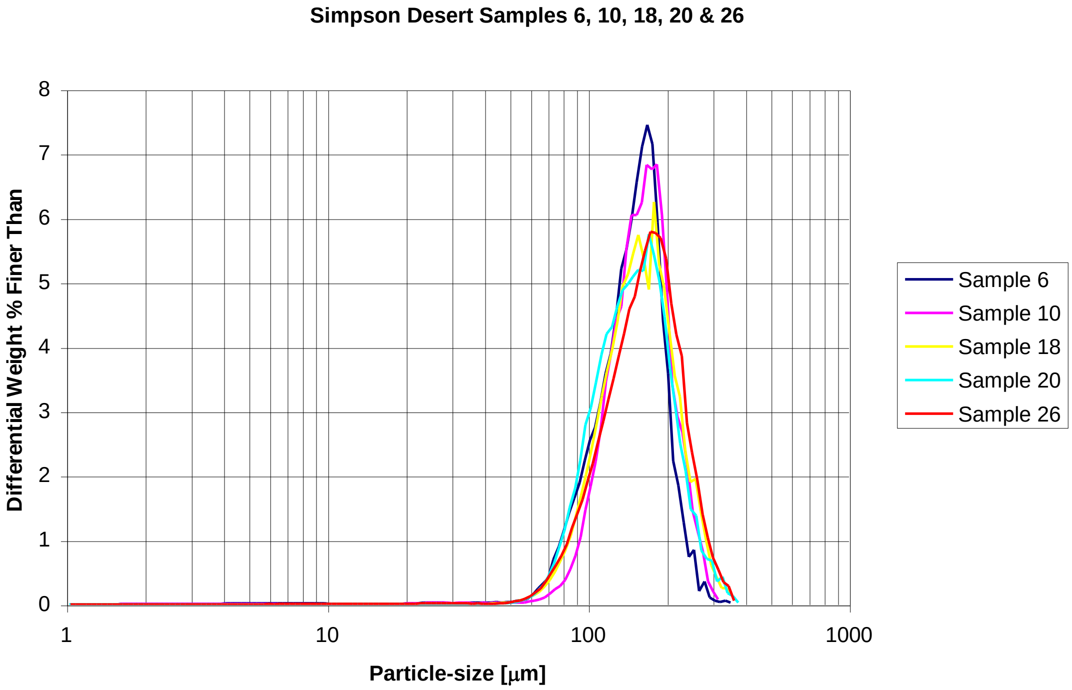


Figure 4-19: PSD's of Samples 6, 10, 18, 20 and 26.

R51 represents Simpson Desert Sample 6
R105 represents Simpson Desert Sample 10
R107 represents Simpson Desert Sample 18
R61 represents Simpson Desert Sample 20
R110 represents Simpson Desert Sample 26

Samples 7, 21, 23 and 27 are from the Simpson Desert region whereas sample 36 is from the Channel Country. All samples are well to moderately well sorted (Figure 4-20). The mean ranges from 212-241 μm.

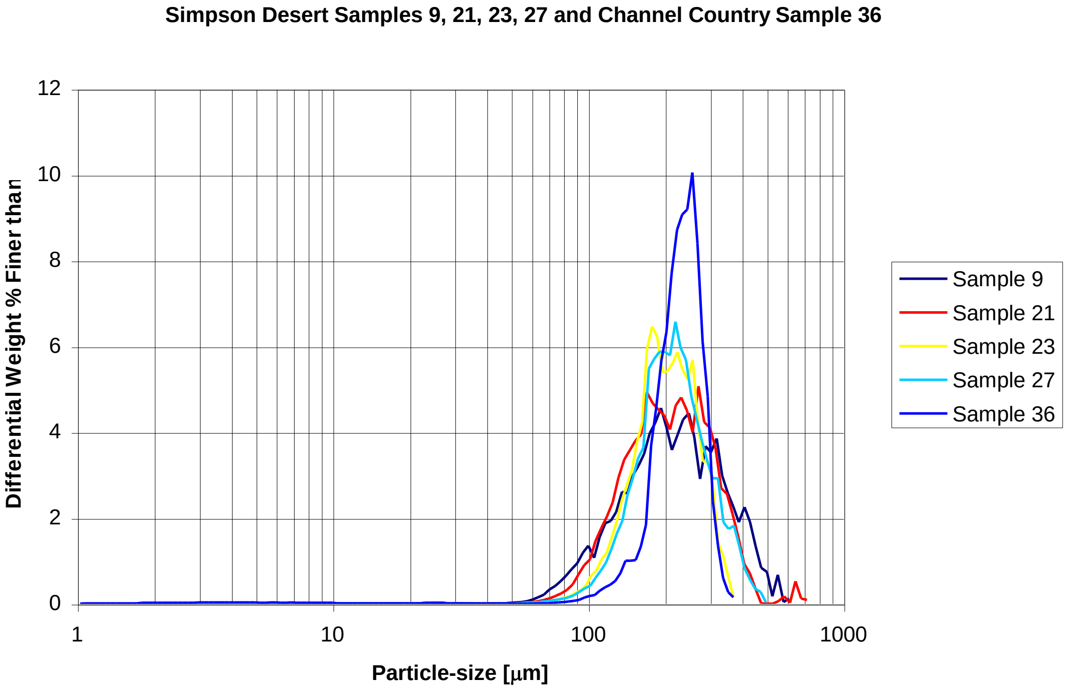


Figure 4-20: PSD's of Samples 9, 21, 23, 27 and Channel Country Sample 36.

R104 represents Simpson Desert Sample 9
R108 represents Simpson Desert Sample 21
R70 represents Simpson Desert Sample 23
R71 represents Simpson Desert Sample 27
R35 represents Channel Country Sample 36 (Windorah)

Samples 7, 19, 30 and 32 are from the Simpson Desert region whereas sample 35 is from the Channel Country. All samples are moderately well sorted with a broad particle-size distribution (Figure 4-21). The mean ranges from 195-310 μm.

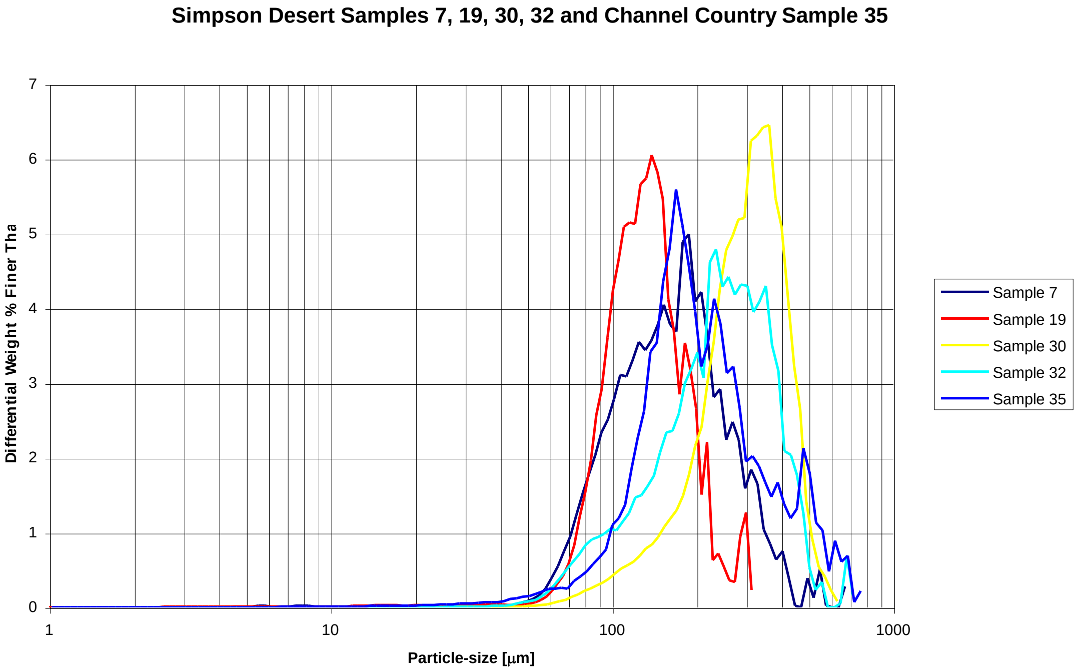


Figure 4-21: PSD's of Samples 7, 19, 30, 32 and 35.

R64 represents Simpson Desert Sample 7
R62 represents Simpson Desert Sample 19
R112 represents Simpson Desert Sample 30
R66 represents Simpson Desert Sample 32
R1 represents Channel Country Sample 35 (Diamantina)

4.7 Statistical analysis

Linear regression analysis was applied to determine the influences of particle-size, sorting, colour, roundness and sphericity have on the rate of dust production. Results show the following:

- approximately 34 percent of dust yield variation is due to particle-size alone.
- approximately 46 percent of dust yield variation is due to standard deviation (sorting) alone.
- approximately 6 percent of dust yield variation is due to colour alone.
- approximately 8 percent of dust yield variation is due to roundness alone.
- approximately 4 percent of dust yield variation is due to sphericity alone.

In addition, a stepwise multiple regression analysis was utilised to determine which combination of independent variables have the greatest influence on dust production. The outcome from this analysis shows that standard deviation (SD) and particle roundness account for 59 percent of the variation in dust yield (Table 4-5).

Table 4-5: Influence of size, sorting, colour, roundness and sphericity on dust production.

Particle-size	Standard Deviation	Colour	Roundness	Sphericity	R^2=Impact on Dust
x	x				0.470
x		x			0.339
x			x		0.364
x				x	0.390
	x	x			0.495
	x		x		**0.591**
	x			x	0.526
		x	x		0.110
		x		x	0.089
			x	x	0.100

The following average prediction formula for dust production is the outcome of this analysis:

Dust = -0.41076 + 0.00331 (SD) + 0.2224 (Roundness)

With this formula it is possible to predict the potential dust yield of other dune sand samples with simular sediment characteristics.

CHAPTER 5

DISCUSSION

5.1 Dust production rates

The aim of this research project was to undertake a laboratory study to investigate the potential for the aeolian abrasion of natural dune sands to produce fine particles (dust) and to establish if this is a significant source of dust during saltation. The size, shape and composition of the sediments, from which the fine particles are derived, are discussed as these are considered to impact upon the nature and rate of dust production.

Laboratory abrasion of natural dune sand grains showed that there are three possible sources of fine material:

1. Small particles initially present in the natural sand population and released during saltation. These resident fines (>63 µm) are fine whole quartz particles and larger fragments derived from the fracture of coarser material (Pye, 1989; Assallay, 1998; Bullard *et al.,* 2003).
2. Fine particles (10-63 µm) produced by chipping and spalling from larger grains (Wright *et al.,* 1998).
3. Fine particles (<10 µm) derived from the removal of clay skins and iron oxide coatings from the surface of quartz grain (Gillette and Walker, 1977).

Microscopic analyses of the collected dust verified that coarse and fine particles were produced during the abrasion experiments and released as dust (Figure 4-6 and 4-7). Quantification of the collected dust into the three main size categories was not part of this study.

Previous experiments by Whalley *et al.,* (1982), Whalley *et al.,* (1987), Smith *et al.,* (1991), Wright (1993) and Wright (1998) were based on the abrasion of freshly crushed Brazilian quartz, grus sands and Pannonian sands to investigate if loess-size dust in the 20-60µm size range can be produced. The aim of the current study focuses on the potential for aeolian abrasion of natural dune sands to produce fine particles. In particular the extent to which colour, size, sorting, shape and the presence of clay skins and iron oxide coatings on grain surfaces influences the amount of dust produced. The results obtained from the current study highlights the fact that the use of sediments with different particle characteristics in abrasion experiments influences dust production yield outcomes.

5.1.1 Parent sand roundness

The abrasion experiments of the current study yielded between 0.41-0.98 % of fines of the initial sample weight. The results contrast with those of Whalley *et al.,* (1982), Whalley *et al.,* (1987), Smith *et al.,* (1991), Wright (1993) and Wright (1998), which produced between 1.55 to 27.7 % of the initial sample weight. These differences can largely be attributed to the different starting characteristics of the material used for the abrasion, which reflect the quite different objectives of their research compared with the current project. Whalley *et al.,* (1982), Whalley *et al.,* (1987), Smith *et al.,* (1991), Wright (1993) and Wright (1998) focussed on loess-sized quartz silt production. The experiments were based on angular sand samples of freshly crushed Brazilian quartz, grus sands and Pannonian sands yielding 1.55 to 27.7 % dust. During abrasion of angular sands, corners and protuberances are removed and are expected to have a significant impact on the total amount of dust yielded. A large degree of rounding is expected to take place. The parent sands used for the current study were sub-angular to sub-rounded with little presence of corners and protuberances, characteristics that are attributed to the sand source and the environment from which the samples were collected. During the abrasion of sub-angular to sub-rounded grains limited dust yields are to be expected and little grain rounding will take place. The different sand grain starting characteristics used for the abrasion experiments may explain the lower dust production rate obtained from natural dune sands. While the dust production rate may not appear to be a significant figure, given the large areas of semi-arid and arid landscapes globally, this process may be a significant source of dust size particles.

5.1.2 Particle-size of parent sands

The particle-size analyses of the unabraded parent samples provided information on the degree of sorting and the mean particle-size. Results indicate that natural dune sand samples are moderately to very well sorted with some variation in mean particle-sizes. This variation can be attributed to the different available sand sources in desert regions, the selective nature of entrainment and the size-dependent mode of transport downwind.

Previous researchers have conducted abrasion experiments using samples that have been sieved to narrow the size range of the parent material. For example Whalley *et al.,* (1982) used particles in the range 710-840 μm for their experiments, Whalley *et al.,* (1987) and Smith *et al.,* (1991) used 350-500 μm, Wright (1993) and Wright *et al.,* (1998) used 250-500 μm and Kuenen (1960) used 400-2000 μm. The experiments undertaken in this study were based on the abrasion of natural dune sands that approximate the "real life situation". Kuenen (1960) stated that by using coarse particles and eliminating fine sands from the abrasion experiments results in larger amounts of dust production than would be expected from the abrasion of natural, mixed sediment populations. This study verifies the contention of Kuenen (1960) that the exclusion of fine materials may influence dust production. The collision dynamics in the abrasion chamber has been altered resulting in the production of coarser material due to chipping, spalling and breakage of larger particles. Whereas during abrasion of a natural sand sample that includes fines, smaller particles may undergo whole particle splitting due to the relative force exerted by coarser particles on smaller particles (Bullard *et al.,* 2003). During this process, coarser particles may either remain unchanged or receive only minimal abrasion. Results from this study show that abrasion of a natural sand sample produces less dust but also the dust particle-size is reduced.

5.1.3 Experimental Conditions

The abrasion chamber utilised is the same design as that used by Whalley *et al.,* (1982), Whalley *et al.,* (1987), Smith *et al.,* (1991), Wright (1993) and Wright *et al.,* (1998). After 72 hours abrasion, a trapping efficiency of 60 percent was attained. This is lower than the 95 percent estimated by Whalley *et al.,* (1987). This difference can be explained by the extended continuous abrasion time of 72 hours compared to the 24 hours used by Whalley *et al.,* (1987). During the extended abrasion time the inside wall of the brass tube (electrostatic precipitator) became covered with dust particles and therefore its capacity to attract additional fines may have been reduced. This difference in the experimental conditions of the two apparatus does not however affect the dust production results. The remaining 40 percent of dust was collected in a water bath and included in the overall dust production weight for each sample. The abrasion apparatus set-up by Whalley *et al.,* (1987) does not include a water bath to collect any fines, which have bypassed the precipitator.

Previous studies using the abrasion chamber to simulate the abrasion process have not tested the replicability. Abrading samples 7, 20 and 32 for 72 hours three times tested the replicability of the method. The amount of material trapped during this time interval was weighed. The amount of dust produced for each of the three sand samples varied by 8.0 % for sample 7, 9.9% for sample 20 and 8.8% for sample 32. A degree of variation is expected because very small amounts of dust are produced from abrasion. Individual grain fracture or splitting of grains producing fine particles will have a great impact on the total mass of dust produced.

5.2 Impact of coatings upon dust production

In addition to size, sorting and angularity the presence of iron oxide and clay coatings may affect dust production. The parent sands used for this study were collected from Simpson Desert and Channel Country dunes known for their marked variation in colouration (Table 4-1). The colours range from yellow (0) to dark brown (3) to red (15) (Torrent *et al*., 1980). Microscopic examination of individual quartz grains and the acid washing of selected sand samples with 10 % hydrochloric acid and stannous chloride (Newsome and Ladd, 1999) showed that the quartz grains are either clear or frosted. The colouration on the quartz grains is attributed to the presence of iron-rich oxides and clay coatings (Figure 4-4 to 4-6). The degree of redness reflects the contribution of haematite, a very common iron oxide in soils of the arid and semi-arid regions (Gardner, 1981; Gardner and Pye, 1981; Taylor *et al.,* 1983; Goudie, 1993). A yellow-brown colour on the quartz grains signals the presence of goethite, an iron oxide often present together with haematite.

There has been some debate in the literature as to whether the iron-rich oxides and clay coatings may be removed during saltation and provide a source of fine material additional to that produced by the rounding and breakage of parent sand grains (Folk, 1976; Walker, 1979; Wopfner and Twidale, 2001). Folk (1976) stated that the saltating population of sand grains (100-500 μm) in the Simpson Desert is redder than the coarser grains. In his view yellowish limonitic surficial "fluff" and carbonaceous specks do not accumulate on the grain surface of this size or are abraded off during saltation but are present on coarser grains. Walker (1979) suggests that aeolian abrasion has the potential to remove clay coatings from coarse grains because the rate of abrasion is greater on these than on finer grains. Coatings on smaller grains are less easily removed. Wopfner and Twidale (2001) commented that fluvial transportation is a more effective method of removing clay coatings than aeolian abrasion. The results from the current study suggest that aeolian abrasion has the potential to remove clay and iron oxide coatings. Petrological microscopic examination of the fine particles produced by abrasion showed them to comprise of iron oxides, clay particles and quartz fragments.

Further support for the contention that iron oxide and clay coatings are removed from the parent grain by abrasion is provided when comparing unabraded with abraded sand grains. Abraded sand grains are paler in colour (lighter hues), which is attributed to the removal of iron oxide and clay coatings from the grain surface (Table 4-1 and Figure 4-1). Similar trends were observed by McTainsh (1985), Shao *et al.*, (1993) and Bullard *et al.*, (2002). These findings suggest that during aeolian abrasion iron oxide and clay coating are removed and therefore makes these a potentially significant source of dust particles.

The incorporation of a stepwise multiple regression analysis made it possible to identify the variables impacting significantly upon the rate of dust production. The main variables influencing the dust production rate are sorting and roundness (Table 4-5). All other variables or combination of variables were less significant. A sand sample that is poorly sorted with angular grains will yield larger amounts of dust than a well sorted sample with rounded grains. Coarser, angular grains have an increased number of protuberances and corners, which may be removed during aeolian abrasion.

The results presented in this study indicate that aeolian abrasion of natural sub-angular to sub-rounded dune sands yields significantly less material than from the abrasion of freshly-crushed quartz and natural angular sands, but the spatial extent of dunefields worldwide makes them potentially significant dust sources at a global scale.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

The aim of this study was to investigate the potential for the aeolian abrasion of natural dune sands to produce fine particles and to see if particle size, sorting, colour, roundness, sphericity and the presence of clay and iron oxide coatings influences the dust production rate. The laboratory abrasion of natural dune sands produced small quantities of dust by chipping, spalling and breakage of sand grains and the removal of clay and iron oxide coatings from the surfaces of quartz grains. A statistical analysis assessing the influence particle size, sorting, colour, roundness and sphericity have on the dust production rate suggests that the degree of sorting and the roundness of grains present within a sample are the most influential components.

This research project demonstrates that there is considerable potential for aeolian abrasion to produce fine particles from natural dune sands. The amount of abraded material is less than that generated from the abrasion of freshly crushed quartz and natural angular sands, but the widespread spatial extent of natural dune sands both in Australia, and worldwide, makes these a potentially significant source of dust particles.

6.2 Recommendation for further research

This research project has raised an important issue about the importance of natural sand abrasion as a potential source of dust-size material. Previous laboratory experiments were based on the abrasion of angular sands with a particle-size range >250 μm. Future research needs to look at the abrasion of natural angular sands, over a wide particle-size range, so as to provide a better understanding of the influence angularity has on the rate of dust production.

The results of this study suggest that the degree of sorting of a sand sample also impacts on the abrasion rate. Additional abrasion experiments, using poorly sorted sand samples are expected to verify the findings that fine material production is related to sorting.

As part of this study particle-size analyses were conducted on the unabraded whole sample. Additional particle-size analyses need to be undertaken on the abraded sands remaining in the test tube chamber at the end of the experimental run. This should show any changes in particle-size characteristics due to abrasion. Particle-size analyses on the collected dust particles are expected to show that the majority of dust particles produced are derived from clay skins and iron oxide coatings rather than quartz fragments.

The use of a QemSCAN (Quantitative Evaluation of Mineralogy with SCANning Electron Microscopes) from the CSIRO could prove useful in the identification, characterisation and quantification of the dust fractions, i.e. separating out clay skins and iron oxide coatings from quartz fragments (Sutherland *et al.,* 1987).

REFERENCES

Al-Saleh, S. and Khalaf, F.I., 1982; Surface texture of quartz grains from various recent sedimentary environments in Kuwait. *Journal of Sedimentary Petrology,* **52**, 215-26.

Anderson, G.E., 1926; Experiments on the rate of wear of sand grains, *Journal of Geology*, **34**, 144-158.

Anton, D. and Ince, F., 1986; A study of sand colour and maturity in Saudi Arabia. *Zeitschrift für Geomorphologie, NF.* **30**, 339-356.

Arimoto, R., 2001; Eolian dust and climate: relationships to source, tropospheric chemistry, transport and deposition. *Earth-Science Reviews*, **54**, 29-42.

Assallay, A.M., Rogers, C.D.F., Smalley, I.J. and Jefferson, I.F., 1998; Silt: 2-62 µm, 9-4ϕ. *Earth-Science Reviews,* **45**, 61-88.

Bryson, R.A. and Barreis, I.A., 1967; Possibilities of major climatic modifications and their implications: Northwest India, a case study. *Bulletin American Meteorological Society,* **48**, 136-42.

Bullard, J.E. and White, K., 2002; Quantitative iron oxide coatings on dune sands using spectrometric measurements: an example for the Simpson-Strzelecki Desert, Australia. *Journal of Geophysical Research*, **107**, (B6) 2125 ECV 5-1 to5-11.

Bullard, J.E., McTainsh, G.H. and Pudmenzky, C., 2002; Aeolian abrasion and fine particle production from natural red dune sands: an experimental study. In: Lee, J.A. and Zobeck, T.M., Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies, Texas Tech University, Lubbock, Texas, USA, Publication 02-2, pp.14-17.

Bullard, J.E., McTainsh, G.H. and Pudmenzky, C., 2003; Aeolian abrasion and fine particle production from natural red dune sand: an experimental study. *Sedimentology*, submitted.

Butler, B.E. and Churchward, H.M., 1983; Aeolian Processes, In: *'Soils: an Australian* viewpoint'. Division of Soils, CSIRO, pp. 91-99. (CSIRO: Melbourne/Academic Press: London).

Cailleux, A., 1952; L'indice de emousée des grain de sable et grès. *Revue de Géomorphologie Dynamique,* **2**, 78-87.

Chapman, F. and Grayson, H.J., 1903; On "red rain", with special reference to its occurrence in Victoria. With a note on Melbourne dust. *Victorian Naturalist*, **20**, 17-32.

Choun, H.F., 1936; Dust storms in the south-eastern Plains area. *Monthly Weather Review*, **64**, 195-199.

Cooke, R., Warren, A. and Goudie, A., 1993; Aeolian sediments, In: Desert Geomorphology. pp. 307-320, UCL Press, London.

Coulter Electronics Limited, 1988; 'Reference Manual for the Coulter Multisizer'. Luton, England.

Croke, J.C., Magee, J.M., Price, D.M., 1998; Stratigraphy and sedimentology of the lower Neales River, West Lake Eyre, Central Australia: from Palaeocene to Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **144**, 331-350.

Duce, R.A., Liss, P.S., Merrill, J.T., Atlas, E.L., Buat-Menard, P., Hicks, B.B., Miller, J.M., Prospero, J.M., Arimoto, R., Church, T.M., Ellis, W., Galloway, J.N., Hansen, L., Jickells, T.D., Knap, A.H., Reinhard, K.H., Schneider, B., Soudine, A., Tokos, J.J., Tsunogai, S., Wollast, R. and Zhou, M., 1991; The atmospheric input of trace species to the world ocean. *Global Biogeochemical Cycles*. **5**, 193-259.

Folk, R.L., 1971; Longitudinal dunes of the northwestern edge of the Simpson Desert, Northern Territory, Australia, 1. Geomorphology and grain size relationships. *Sedimentology*, **16**, 5-54.

Folk, R.L., 1976; Redding of desert sands: Simpson Desert, N.T. Australia. *Journal of Sedimentary Petrology*, **46**, 604-615.

Folk, R.L., 1978; Angularity and silica coatings of Simpson Desert sand grains, Northern Territory, Australia. *Journal of Sedimentary Petrology*, **48**, 611-624.

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

Gardner, R.A.M., 1981; Redding of dune sands – evidence from southeast India. *Earth Surface Processes and Landforms*, **6**, 459-468.

Gardner, R.A.M. and Pye, K., 1981; Nature, origin and palaeoenvironmental significance of red coastal and red desert sand dunes. *Progress in Physical Geography*, **5**, 514-534.

Gillette, D.A. and Walker, T.R., 1977; Characteristics of airborne particles produced by wind erosion of sandy soil, High Plains of Texas. *Soil Science*, **123**, 97-110.

Gomes, L., Bergametti, G., Caudé-Gaussen, G. and Rognon, P., 1990; Submicron desert dusts: a sandblasting process. *Journal of Geophysical Research*, **95**, 13927-

13935.

Goudie, A.S., 1978; Dust storms and their geomorphological implications. *Journal of Arid Environments*, **1**, 291-310.

Goudie, A.S. and Watson, A., 1981; The shape of desert sand dune grains. *Journal of Arid Environments*, **4**, 185-190.

Goudie, A.S., Warren, A., Jones, D.K.C. and Cooke, R.U., 1987; The character and possible origin of the aeolian sediments of the Wahiba Sands. *Geographical Journal*, **153**, 231-256.

Goudie, A.S., Anderson, M., Burt, T., Lewin, J., Richards, K., Whalley, B. and Worsley, P., 1991; *Geomorphological Techniques*. 2nd. Edition, Unwin Hyman, London, UK.

Goudie, A.S., Stokes, S., Livingstone, I., Bailiff, I.K. and Allison, R.J., 1993; The nature, age and Sedimentology of relict dunes in West Kimberley, N.W. Australia. *Geographical Journal*, **159**, 306-317.

Greeley, R. and Iversen, J.D., 1985; Wind as a geological process on Earth, Mars, Venus and Titan, Cambridge Planetary Science Series No. 4, Cambridge University Press, Cambridge, 291.

Greene, R., Gatehouse, R., Scott, K. and Chen, X.Y., 2001; Symposium report: Aeolian dust – implications for Australian mineral exploration and environmental management. *Journal of Soil Research*, **39**, 1-6.

Idso, S.B., 1976; Dust storms. *Scientific American*, **235**, 4, 108-111, 113-114.

Kiefert, L., 1995; Characteristics of wind transported dust in Eastern Australia. unpublished PhD Thesis, Griffith University, Brisbane, Australia.

Knight, S.H., 1924; Eolian abrasion of quartz grains. *Geological Society of American Bulletin*, **35**, 107-108.

Knight, A.W., McTainsh, G.H. and Simpson, R.W., 1995; Sediment loads in an Australian dust storm: Implications for present and past dust processes. *Catena*, **24**, 195-213.

Krinsley, D.H. and Doornkamp, J.C., 1973; Atlas of quartz sand surface textures, Cambridge, England.

Krinsley, D.H. and Smalley, I.J., 1973; Shape and nature of small sedimentary quartz particles. *Science*, **180**, 1277-1278.

Kuenen, Ph.H., 1960; Experimental abrasion 4: Eolian action. *Journal of Geology*, **68**, 427-449.

Kuenen, Ph.H., 1969; Origin of quartz silt. *Journal of Sedimentary Petrology*, **39**, 1631-1633.

Levin, A., Ganor, E. and Gladstein, V., 1996; The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean. *Journal of Applied Meteorology*, **35**, 1511-1523.

Liversidge, A., 1902; Meteoric dusts, New South Wales, Royal Society of NSW. *Journal and Proceedings*, **36**, 241-285.

Livingstone, I. and Warren, A., 1996; Aeolian Geomorphology: An Introduction. Addison Wesley Longman, Harlow, UK.

Mabbutt, J.A. and Sullivan, M.E., 1968; The formation of longitudinal dunes: evidence from the Simpson Desert. *Australian Geographer*, **10**, 483-87.

Margolis, S.V. and Krinsley, D.H., 1971; Submicroscopic frosting on Eolian and subaqueous quartz sand grains. *Geological Society of America, Bulletin* **82**, 3395-406.

Marsland, P.S. and Woodruff, J.G., 1937; A study of the effect of wind transportation on grains of several minerals. *Journal of Sedimentary Petrology*, **7**, 18-30.

McLane, M., 1995; Sedimentology, Oxford University Press, New York.

McMillan, S., 2002; Dust storm engulfing the town of Griffith, NSW. Sent by Samantha.J.McMillan@transport.qld.gov.au [12 November 2002].

McTainsh, G.H., 1985; Desertification and dust monitoring in West Africa. *Desertification Control Bulletin*, **12**, 26-33.

McTainsh, G.H., 1989; Quaternary aeolian dust processes and sediments in the Australian region. *Quaternary Science Review*, **8**, 235-253.

McTainsh, G.H., Lynch, A.W. and Burgess, R.C.,1990; Wind erosion in Eastern Australia. *Australian Journal of Soil Research*, **28**, 323-339.

McTainsh, G.H. and Boughton, W.C., 1993; Land degradation in Australia – An introduction. In: McTainsh, G.H., Boughton, (Ed.), *Land Degradation Processes in Australia*. p 1-15, Longman, Melbourne, Australia.

McTainsh, G.H. and Leys, J., 1993; Soil Erosion by Wind. In: McTainsh, G.H., Boughton, (Ed.), *Land Degradation Processes in Australia*. p 188-233, Longman, Melbourne, Australia.

McTainsh, G.H., Leys, J., Nickling, W. and Lynch, A., 1996; Sediment loads, source areas and soil loss rates during a large dust storm in the Queensland Channel Country, Lake Eyre Basin. *Australian Rangelands Society Conference*, Port

Augusta, South Australia.

McTainsh, G. H., Lynch, A. W. and Hales, R., 1997; 'Particle-Size Analysis of Aeolian Dusts, Soils and Sediments in very small Quantities using a Coulter Multisizer'. *Earth Surface Processes and Landforms*, **22**, 1207-1216.

McTainsh, G.H., Leys, J. and Nickling, W., 1999; Wind erodibility of arid lands in the Channel Country of Western Queensland, Australia. *Zeitschrift für Geomorphologie N.F.*, **116**, 113-130.

McTainsh, G.H. and Tews, K., 2002; Dust storm frequency 1960-1999, unpublished.

McTainsh, G.H., 24 April 2003; Discussion about the Simpson Desert being the dust storm hot spot in central Australia. Personal communication.

Miller, B.V. and Lines, R.W., 1988; Recent advances in particle size measurements: a critical review. *CRC Critical Reviews in Analytical Chemistry*, **20**, 2, 75-116.

Mooney, B., 1999; The relationship between alluvial and aeolian processes on the Diamantina floodplain in the Channel Country, of southwest Queensland. unpublished Honours Thesis, Griffith University, Australia.

Munsell Soil Colour Charts, 1992; Macbeth, Division of Kollmorgen Instruments Corporation, New York.

Newsome, D. and Ladd, P., 1999; The use of quartz microtextures in the study of the origin of sand terrains in Western Australia. *Catena*, **35**, 1-17.

Nickling, W.G., 2002; Desertification: reality or myth, Dept. of Geography, University of Guelph, http://www.geography.uoguelph.ca [15 October, 2002].

Pell, S.D., Chivas, A.R. and Williams, I.S., 2000, The Simpson, Strzelecki and Tirari Deserts: development and sand provenance. *Sedimentary Geology*, **130**, 107-130.

Pettijohn, F.J., 1957; Sedimentary Rocks. Harper and Brothers, USA.

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

Purdie, R., 1984; Land Systems of the Simpson Desert Region, CSIRO Division of Water and Land Resources. Natural Resources Series No. 2, Melbourne, Australia.

Pye, K., 1989; Processes of fine particle formation, dust source regions and climatic changes. In: *Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport* (Eds. M. Leinen and M. Sarntheim), Kluwer, Dordrecht, NATO ASI **Series 282**, 3-30.

Pye, K., 1990; Aeolian dust and dust deposits. Academic Press, London.

Seawifs, 2002; Dust storm event on the 23 October 2002 in Australia. Available at http://www.seawifs.gstc.NASA.gov [24 October, 2002].

Shao, Y., 2000; Physics and modelling of wind erosion, Kluwer Academic Press, Netherlands.

Shao, Y., McTainsh, G.H., Leys, J.F. and Raupach, M.R. 1993; Efficiencies of sediment samplers for wind erosion measurement. *Australian Journal of Soil Research*, **31,** 519-532.

Shotton, F.W., 1937; The Lower Bunter sandstones of north Worcestershire and east Shropshire (England). *Geological Magazine*, **74**, 534-553.

Smalley, I., Viat-Finzi, C., 1968; The formation of fine particles in sandy deserts and the nature of 'desert' loess. *Journal of Sedimentary Petrology*, **38**, 766-774.

Smith, B.J., Wright, J.S. and Whalley, W.B., 1991; Simulated aeolian abrasion of Pannonian sands and its implications for the origin of Hungarian loess. *Earth Surface Processes and Landforms*, **16**, 745-752.

Squires, V.R., 2001; Dust storms and dust devils in South Australia – the driest province of the driest continent on Earth. In: Youlin, Y., Squires, V., Qi, L., (Eds.) *Global Alarm: Dust and Sandstorms from the World's Drylands.* United Nations, pp. 155-166.

Sutherland, D.N., Creelman, R.A., Gottlieb, P., Jackson, B.R., Quittner, V.H., Wilkie, G.J., Zuiderwyk, M.A., Allen, N.R. and McLean, T., 1987;. The Development and Application of QEM*SEM. *Proceedings Chemeca 87*, **2**, 106.1-106.6.

Taylor, R.M., McKenzie, R.M., Fordham, A.W. and Gillman, G.P., 1983; Oxide minerals. *In* ‘Soils: an Australian viewpoint’, Division of Soils, CSIRO, pp. 309-334. (CSIRO: Melbourne/Academic Press: London).

Tegen, I., Hollrig, P., Chin, M., Fung, I., Jacob, D. and Penner, J., 1997; Contribution of different aerosol species to the global aerosol extinction optical thickness: estimates from model results. *Journal of Geophysical Research*, **102**, 23, 895-23, 916.

Tegen, I. and Fung, I., 1995; Contribution to the atmospheric mineral aerosol load from land surface modification. *Journal of Geophysical Research*, **100**, 18707-18726.

Torrent, J., Schwertmann, U. and Schulze, D.G., 1980; Iron oxide mineralogy of some soils of two river terrace sequences in Spain. *Geoderma*, **23**, 191-208.

Twidale, C.R. and Wopfner, H., 1990; Chapter 3 – Dunefields, p. 45-60. In: Tylor, M.J., Twidale, C.R., Davies, M. and Wells, C.B., (Eds.) *Natural History of the* *north- east deserts*. Royal Society of South Australia Inc., Adelaide.

Udden, J.A., 1894; Erosion, transportation and sedimentation performed by the atmosphere. *Journal of Geology*, **2**, 318-331.

Walden, J. and White, K., 1997; Investigation of the controls on dune colour in the Namib Sand Sea using mineral magnetic analyses. *Earth and Planetary Science Letters*, **152**, 187-201.

Walker, T.R., 1979; Red colour in Eolian sands. In: McKee, E.D., (Eds.), *A Study of Global Sand Seas*. USGS Professional Paper **1052**, 62-81.

Wasson, R.J., 1983; Dune sediment types, sand colour, sediment provenance and hydrology in the Strzelecki-Simpson dunefield, Australia. In: Brookfields, M.E. & Ahlbrandt, T.S., (Eds.), *Aeolian Sediments and Processes*. Elsevier, Amsterdam, pp. 165-195.

Wasson, R.J. and Hyde, R., 1983b; A test of Wilson's granulometric control of desert dunes hypothesis. *Earth Surface Processes*, **8**, 301-312.

Wasson, R.J., Fitchett, K., Mackey, B. and Hyde, R., 1988; Large-scale patterns of dune type, spacing and orientation in the Australian Continental Dunefield; *Australian Geographer*, **19**, 89-103.

Whalley, W.B., Marshall, J.R. and Smith, B.J., 1982; Origin of desert loess from some experimental observations. *Nature*, **300**, 433-435.

Whalley, W.B., Smith, B.J., McAlster J.J. and Edwards, A.J., 1987; Aeolian abrasion of quartz particles and the production of silt-size fragments: preliminary results. In: Frostick, L. & Reid, I., (Eds.), Desert Sediments: ancient and modern. *Geological Society Special Publication*, **35**, 129-138.

Williams, O.B. and Calaby, J.H., 1985; The hot deserts of Australia. In: Evanari, M. and Noy-Meir, I., (Eds.), *Deserts of the World.* Elsevier, Amsterdam.

Wilson, P., 1979; Experimental investigation of etch-pit formation on quartz sand grains. *Geological Magazine*, **116**, 477-82.

Wopfner, H. and Twidale, C.R., 1967; Geomorphological history of the Lake Eyre Basin, In: Mabbutt, J.A., (Eds.), *Landform Studies from Australia and New Guinea.* Australia University Press, Canberra, pp. 118-143.

Wopfner, H. and Twidale, C.R., 2001; Australian desert dunes: wind rift or depositional origin? *Australian Journal of Earth Sciences*, **48**, 239-244.

Wright, J., 2001; Making loess-sized quartz silt: data from laboratory simulations and implications for sediment transport pathways and the formation of ‘desert’ loess deposits associated with the Sahara. *Quaternary International*, **76/77**, 7-19.

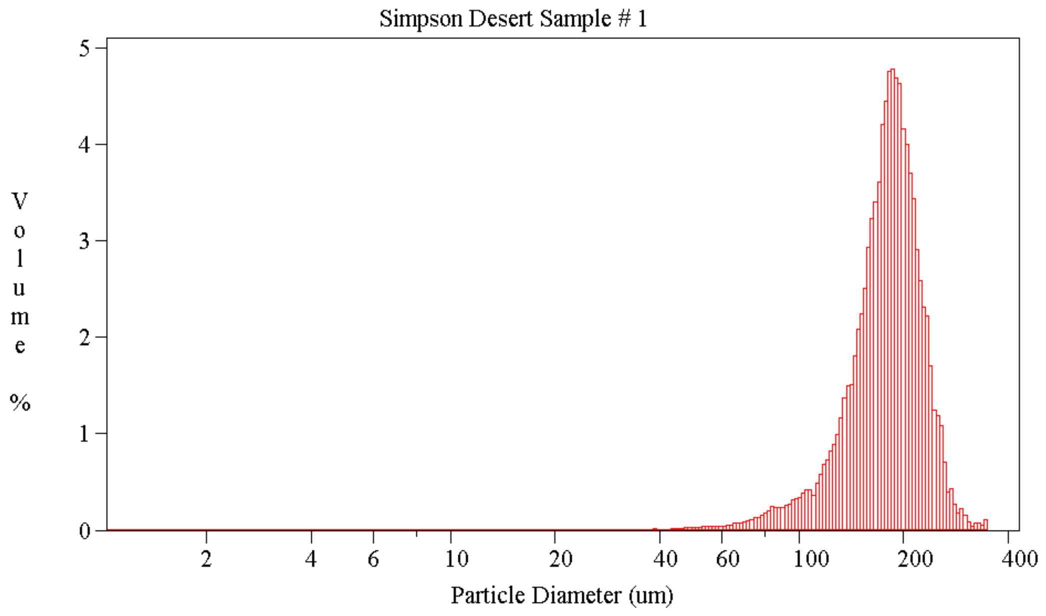
Wright, J., Smith, B.J. & Whalley, W.B., 1998; Mechanisms of loess-sized quartz silt production and their relative effectiveness: laboratory simulations. *Geomorphology*, **23**, 15-34.

Zingg, T., 1935; Beitrag zur Schotteranalyse. *Schweiz. Mineralog. Petrog. Mitt.*, Bd. **15**, pp. 39-140.

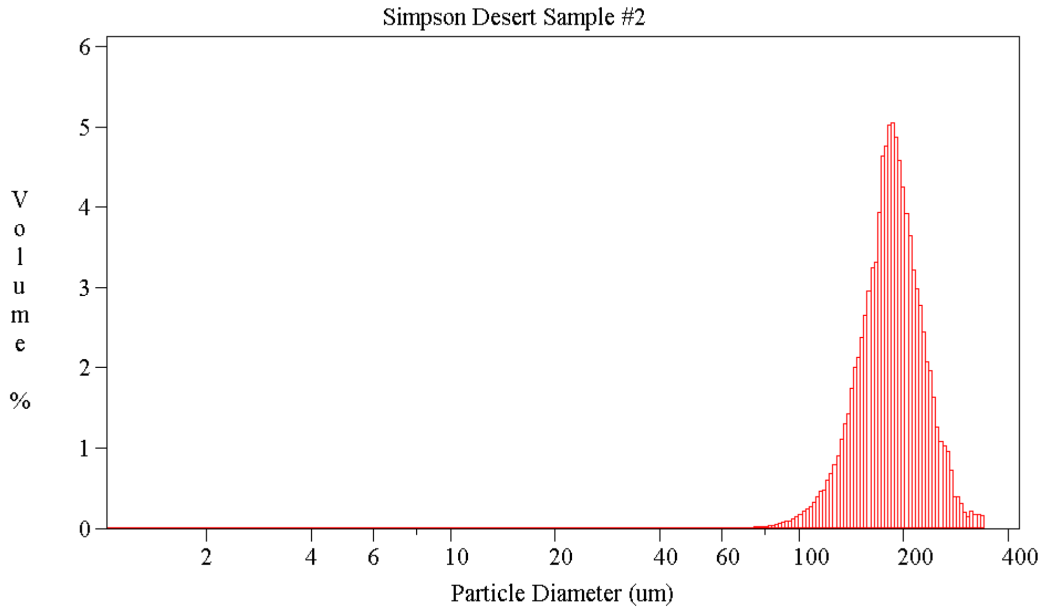
APPENDICES

Appendix A: Particle-size Distributions

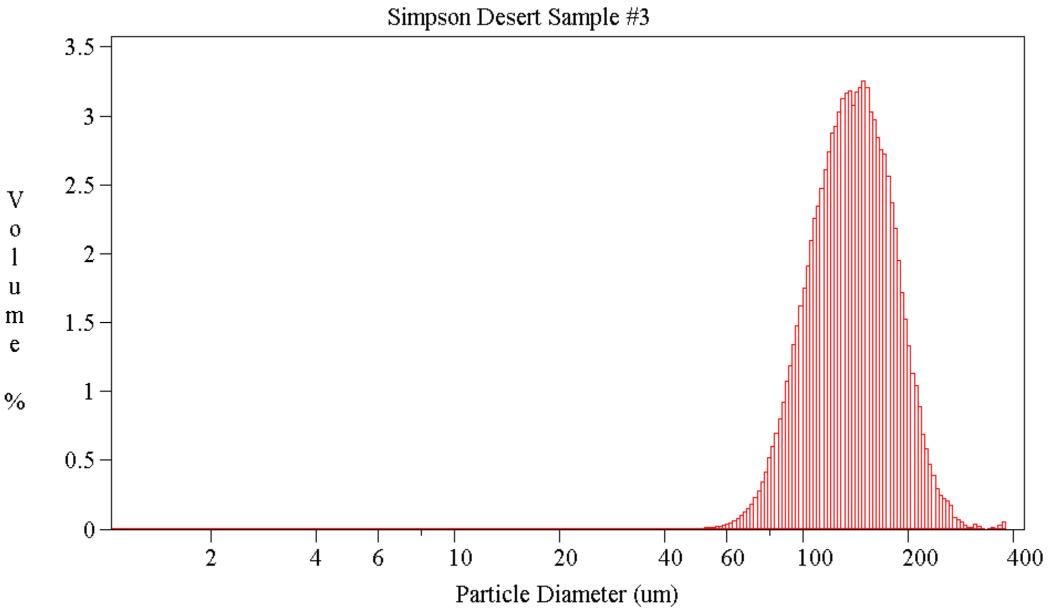
(a)



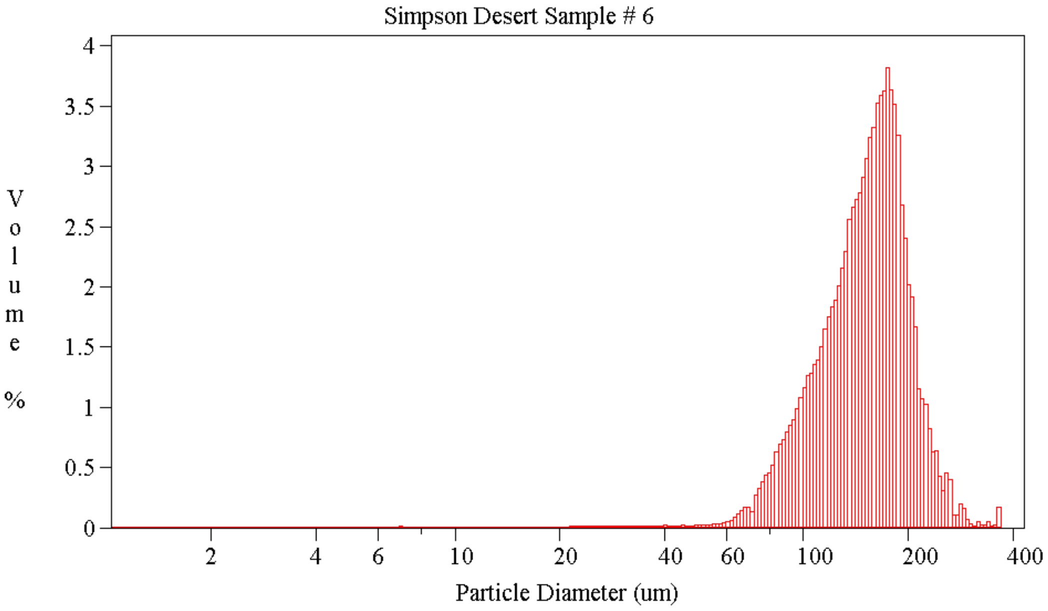
(b)



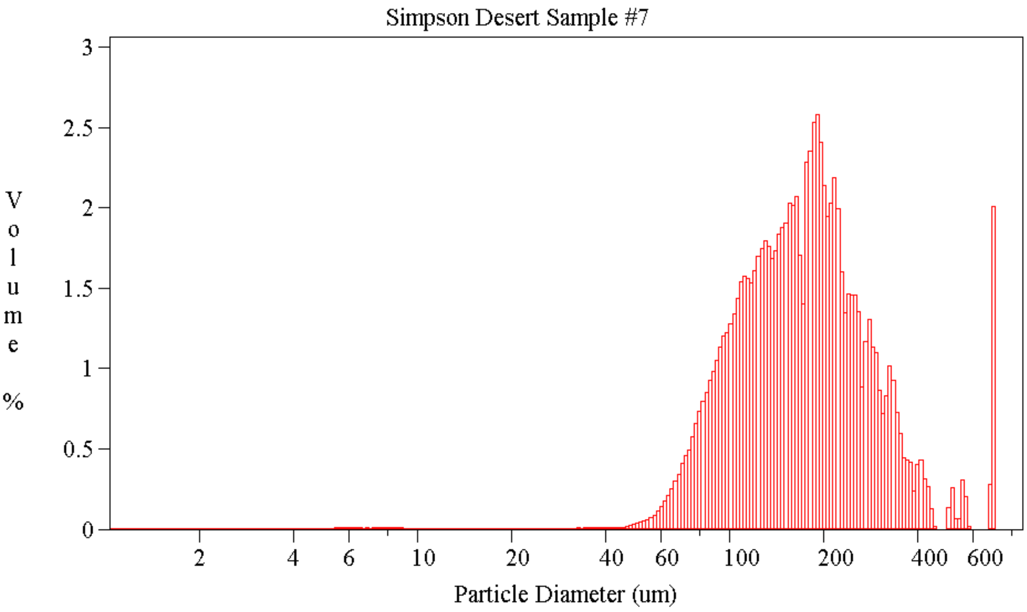
(c)


Simpson Desert Sample #3
Volume %
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

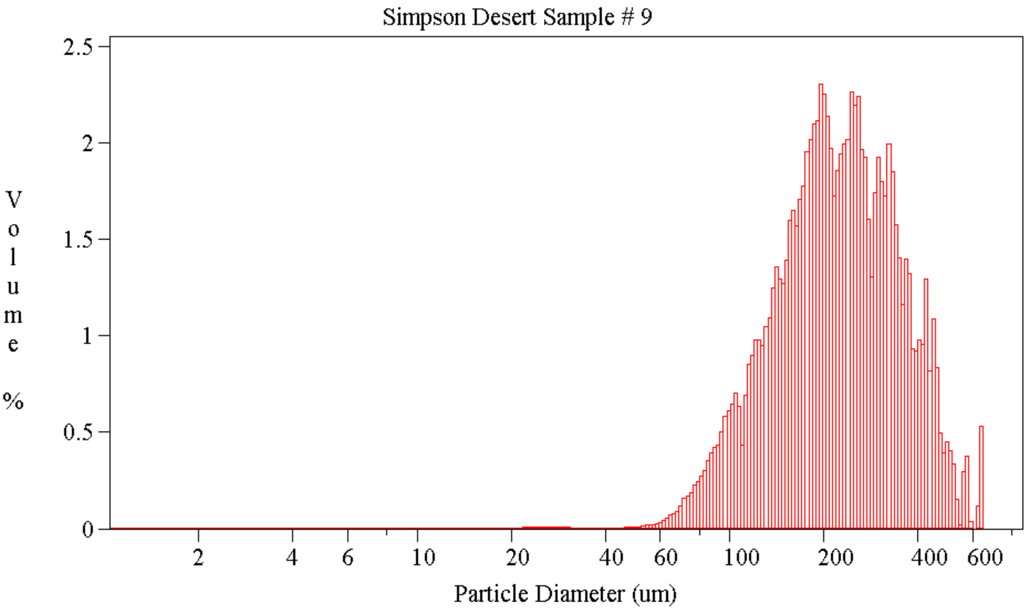
(d)


Simpson Desert Sample # 6
Volume %
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

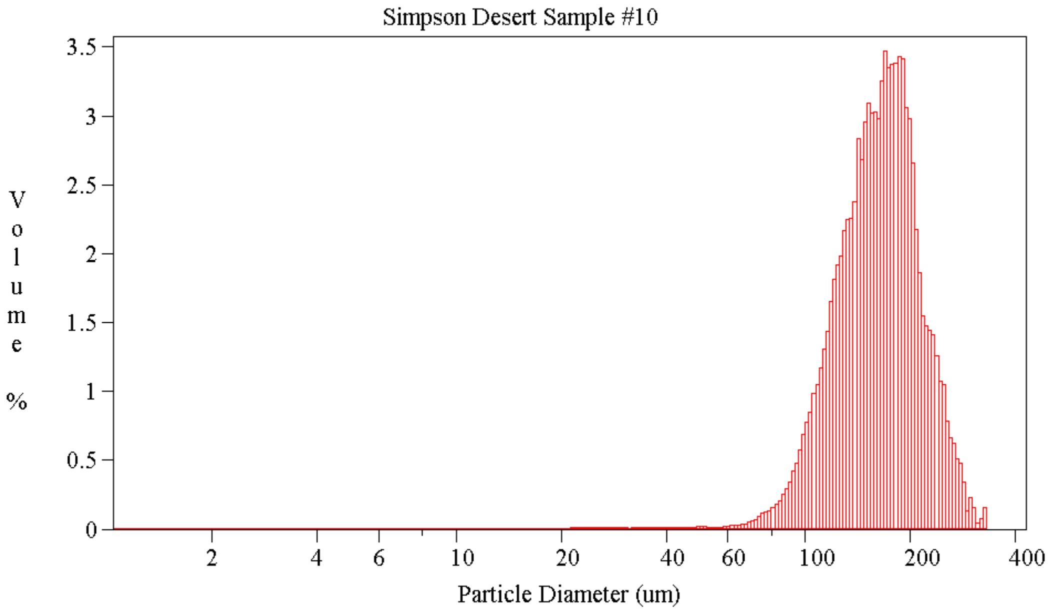
(e)


Simpson Desert Sample #7
V o l u m e %
0
0.5
1
1.5
2
2.5
3
2
4
6
10
20
40
60
100
200
400
600
Particle Diameter (um)

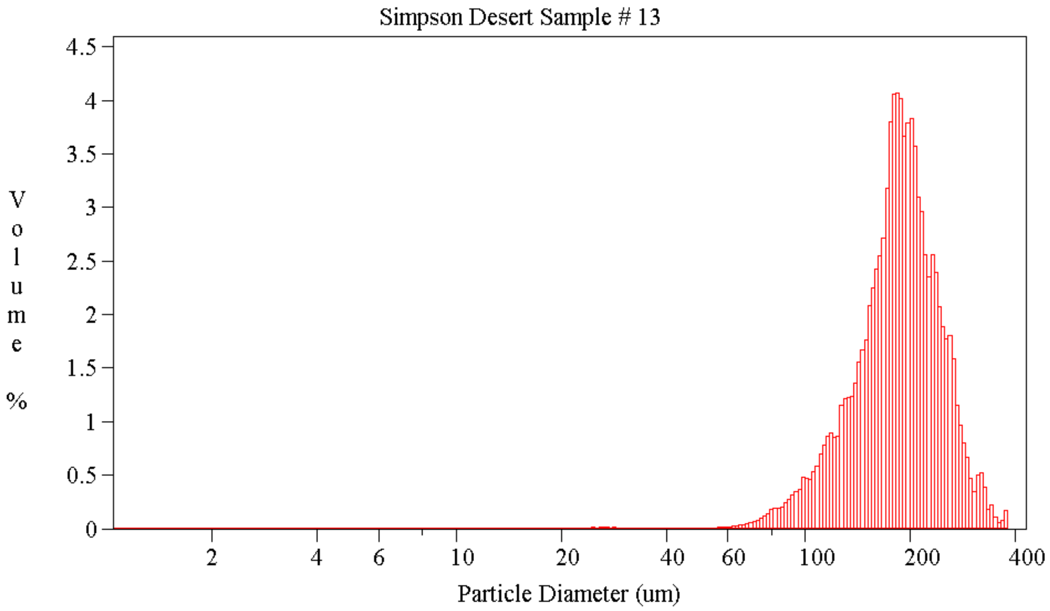
(f)


Simpson Desert Sample # 9
V o l u m e %
0
0.5
1
1.5
2
2.5
2
4
6
10
20
40
60
100
200
400
600
Particle Diameter (um)

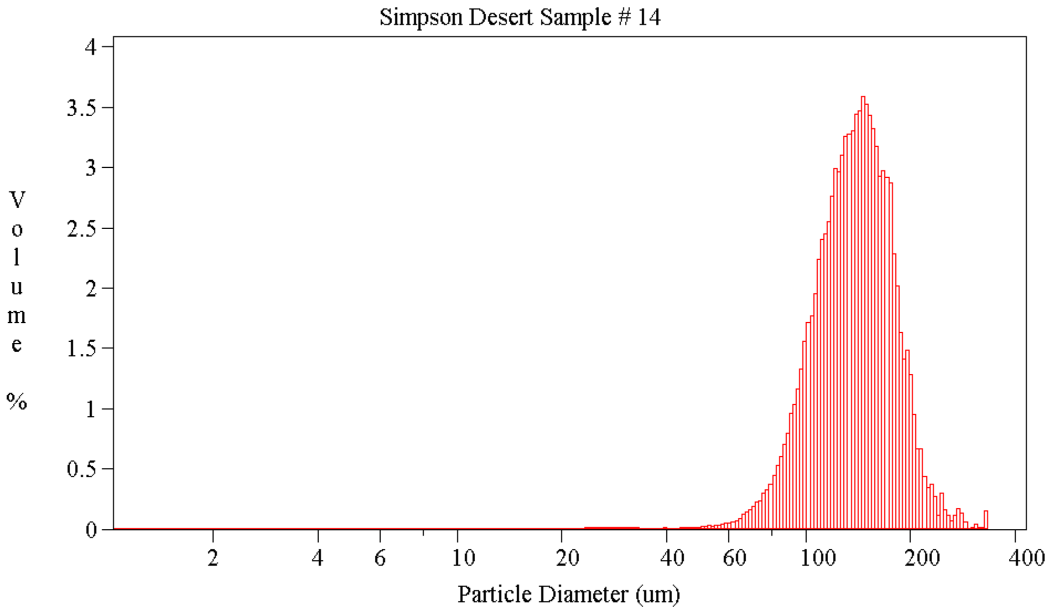
(g)


Simpson Desert Sample #10
3.5
3
2.5
2
1.5
1
0.5
0
V o l u m e %
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

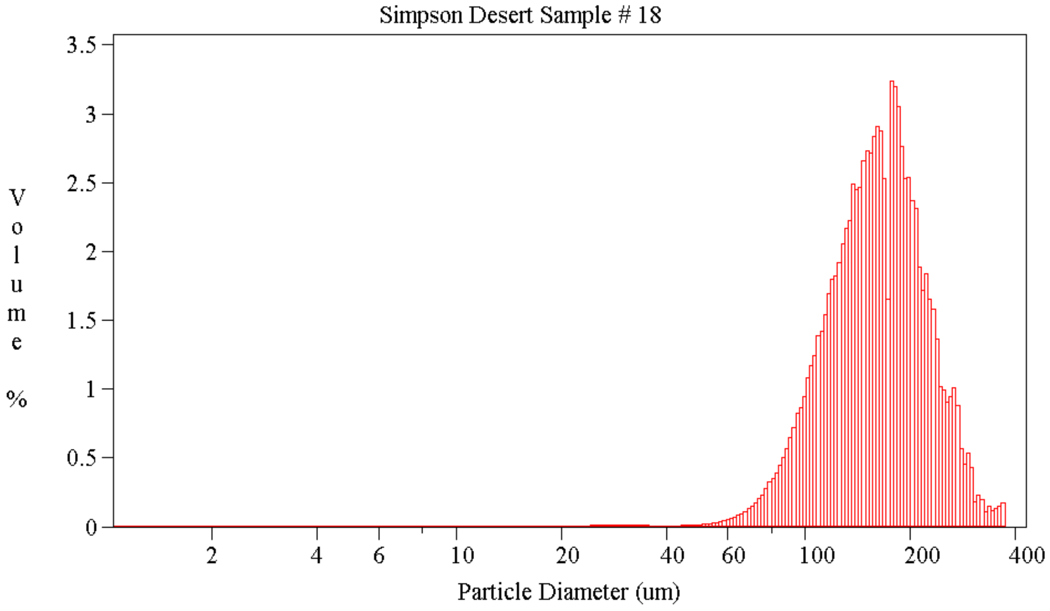
(h)


Simpson Desert Sample # 13
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
V o l u m e %
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

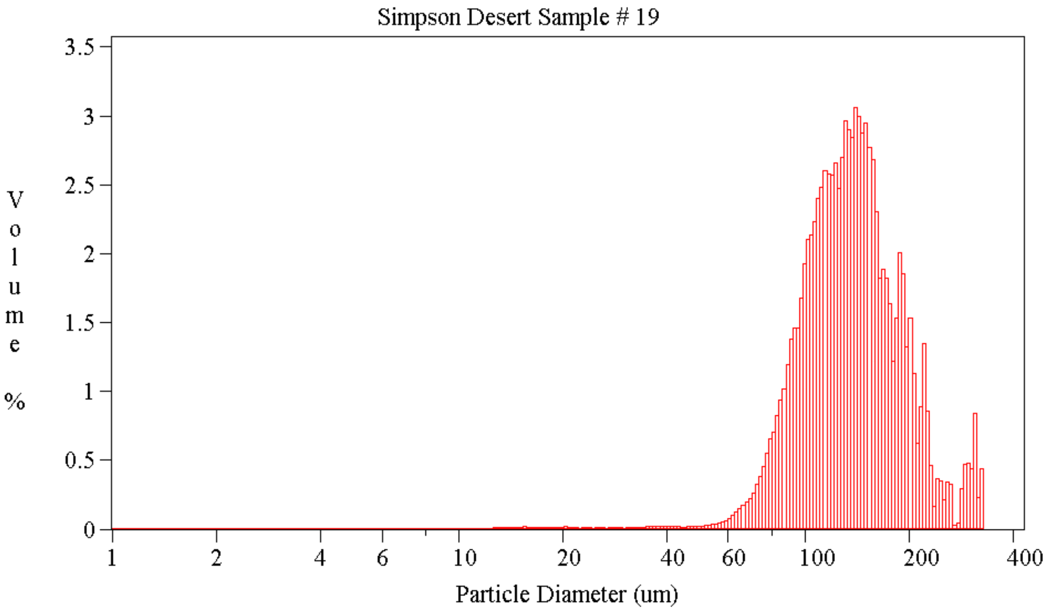
(i)


Simpson Desert Sample # 14
Volume %
0
0.5
1
1.5
2
2.5
3
3.5
4
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

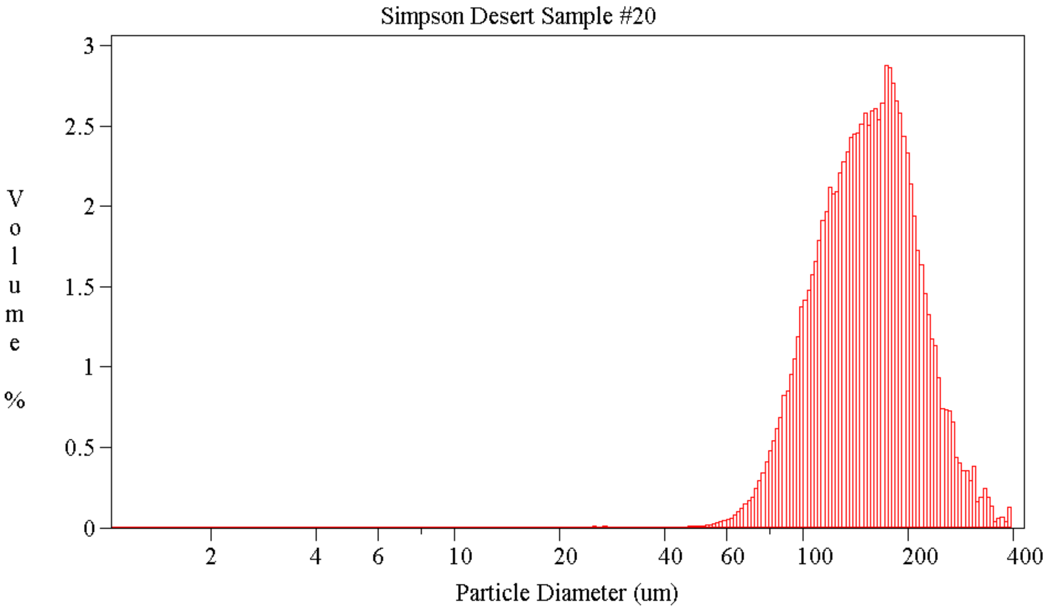
(j)


Simpson Desert Sample # 18
Volume %
0
0.5
1
1.5
2
2.5
3
3.5
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

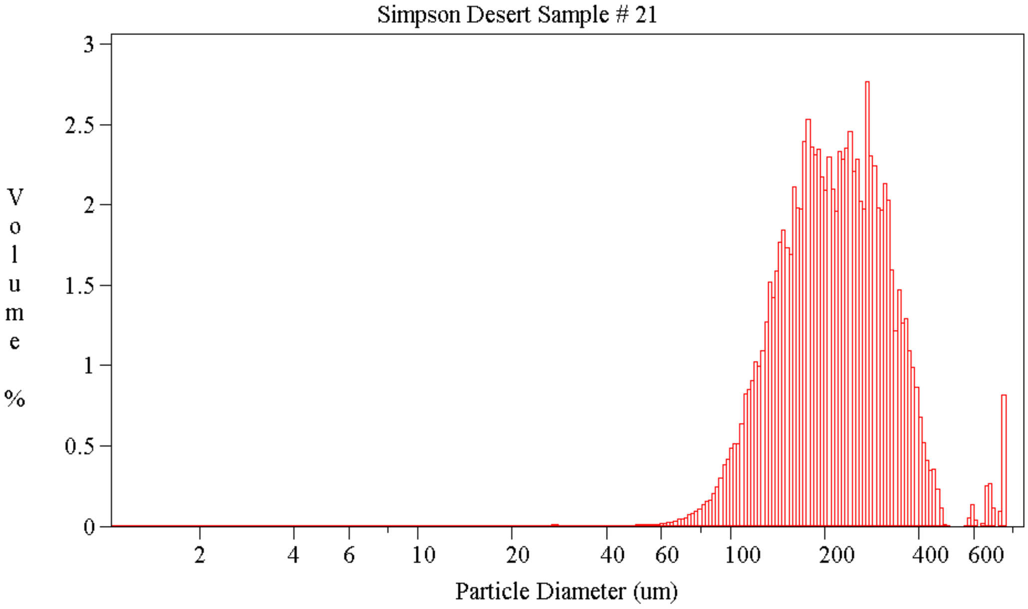
(k)


Simpson Desert Sample # 19
V o l u m e %
3.5
3
2.5
2
1.5
1
0.5
0
1
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

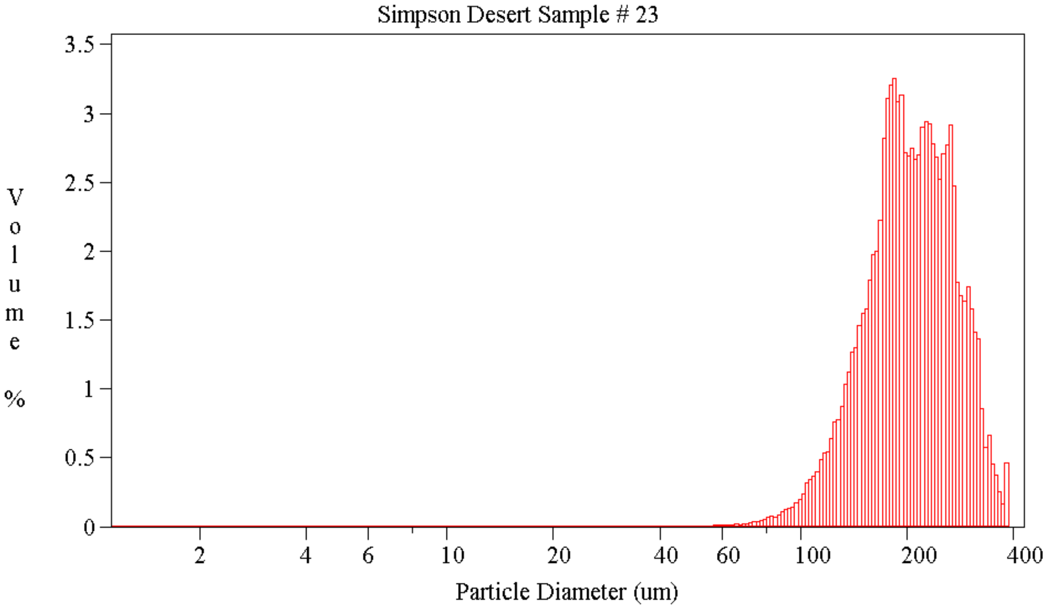
(l)


Simpson Desert Sample #20
V o l u m e %
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

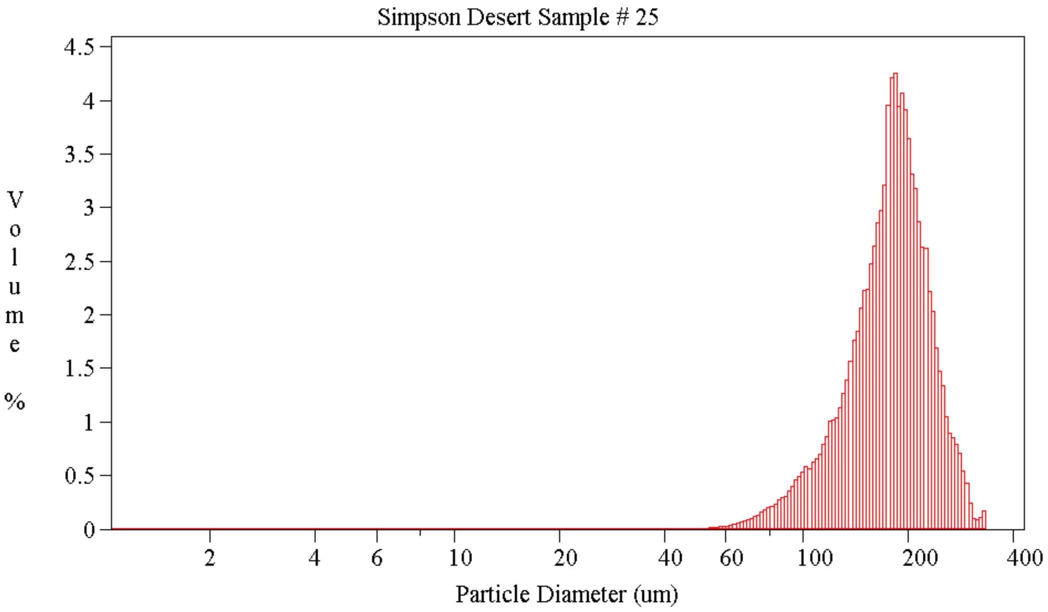
(m)


Simpson Desert Sample # 21
Volume %
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
600
Particle Diameter (um)

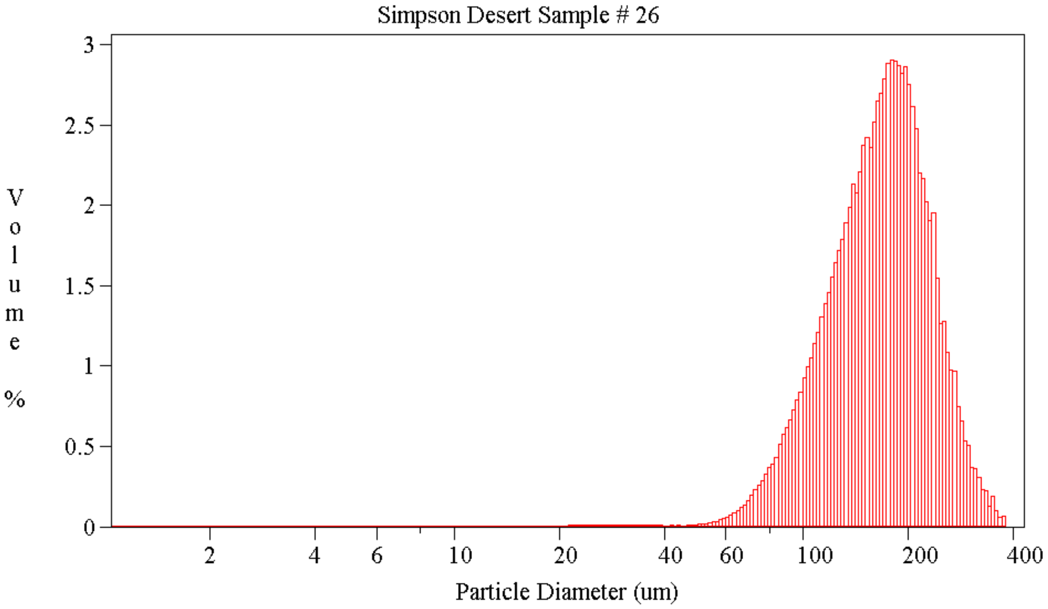
(n)


Simpson Desert Sample # 23
Volume %
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

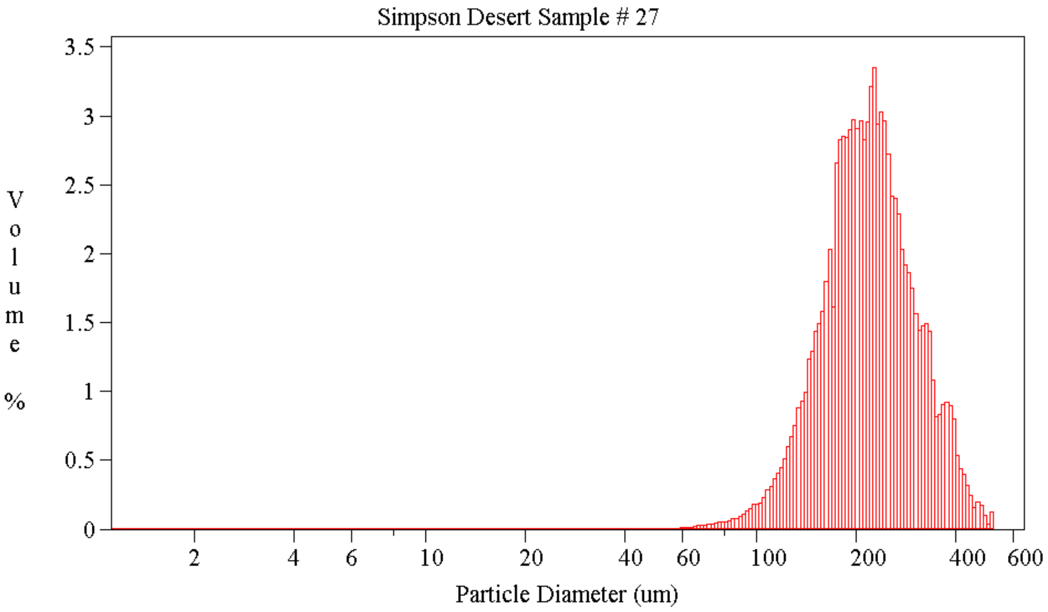
(o)


Simpson Desert Sample # 25
Volume %
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

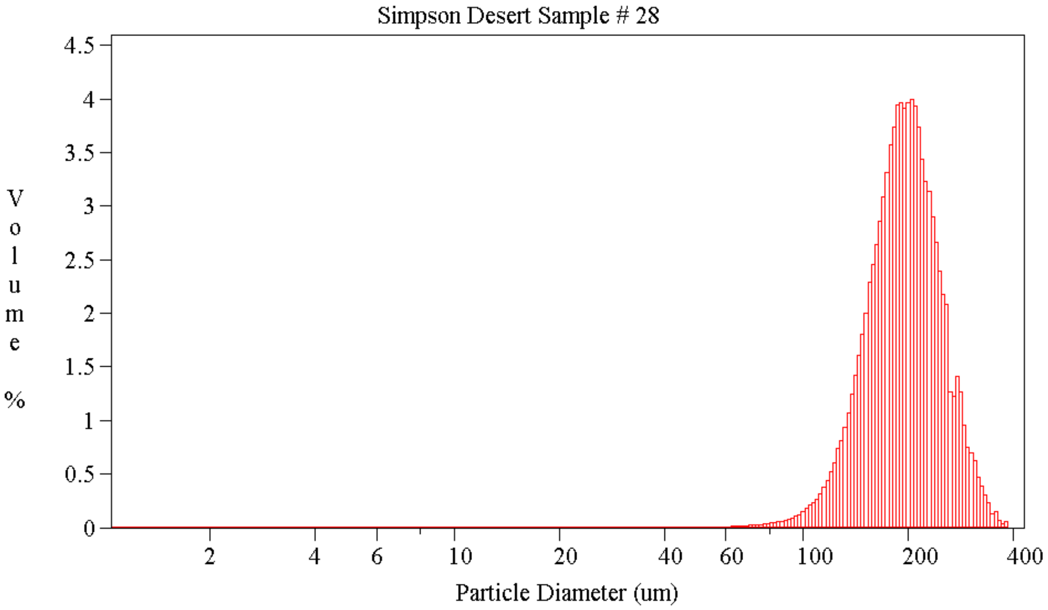
(p)


Simpson Desert Sample # 26
Volume %
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

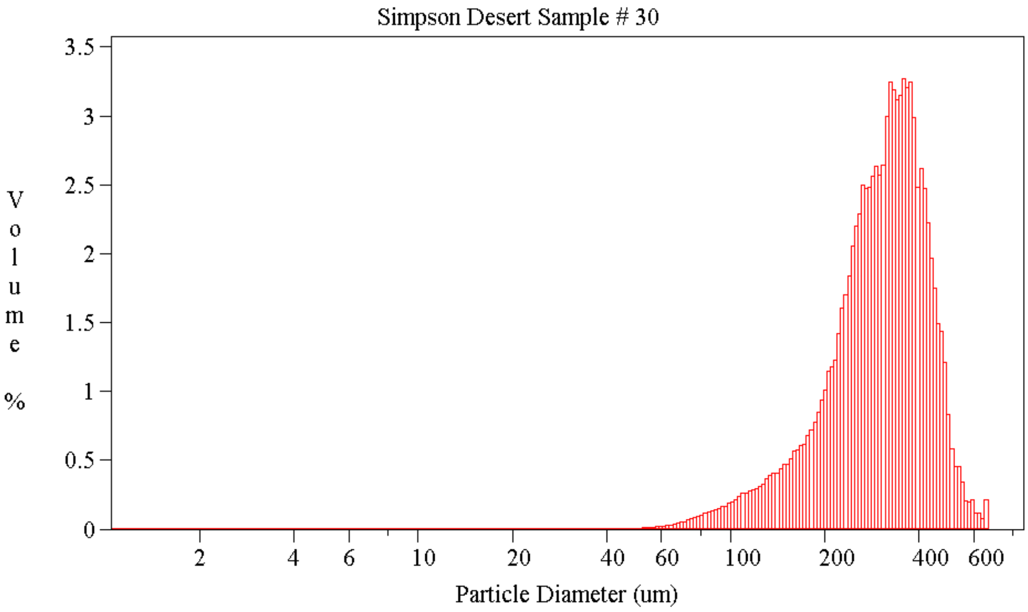
(q)


Simpson Desert Sample # 27
V o l u m e %
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
600
Particle Diameter (um)

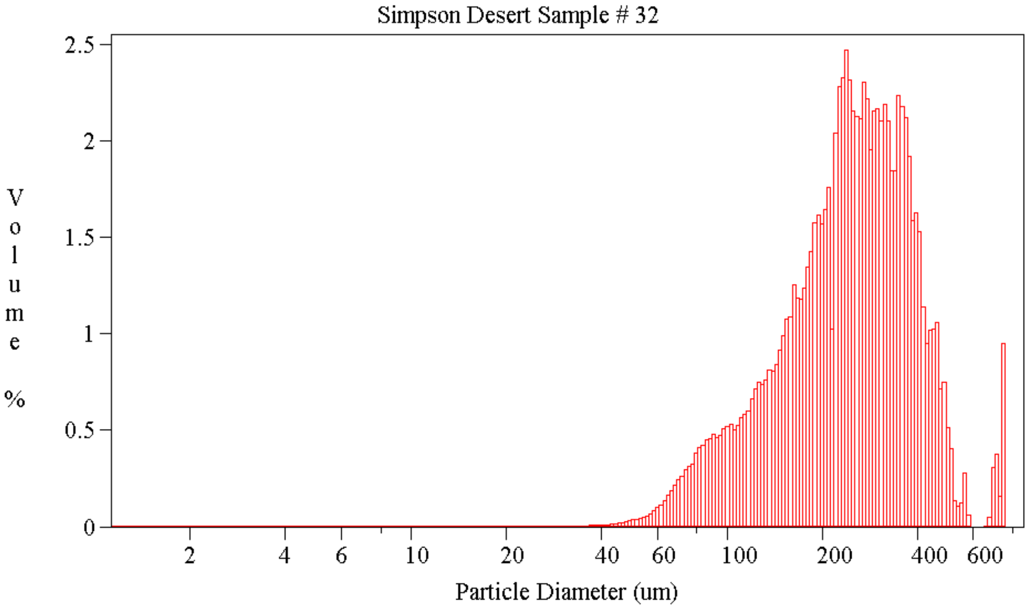
(r)


Simpson Desert Sample # 28
V o l u m e %
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
10
20
40
60
100
200
400
Particle Diameter (um)

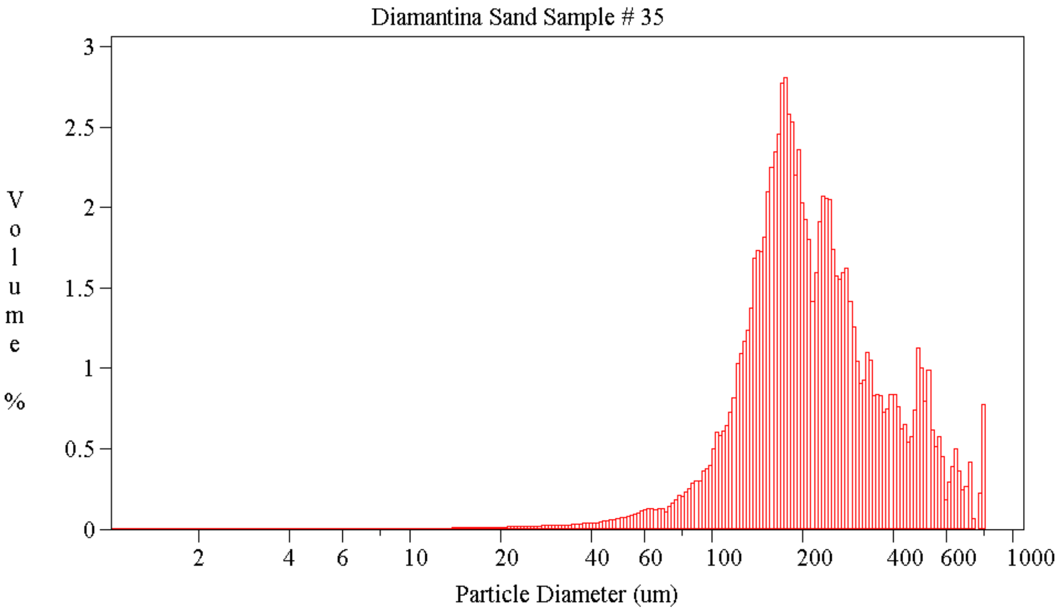
(s)


Simpson Desert Sample # 30
V o l u m e %
0
0.5
1
1.5
2
2.5
3
3.5
2
4
6
10
20
40
60
100
200
400
600
Particle Diameter (um)

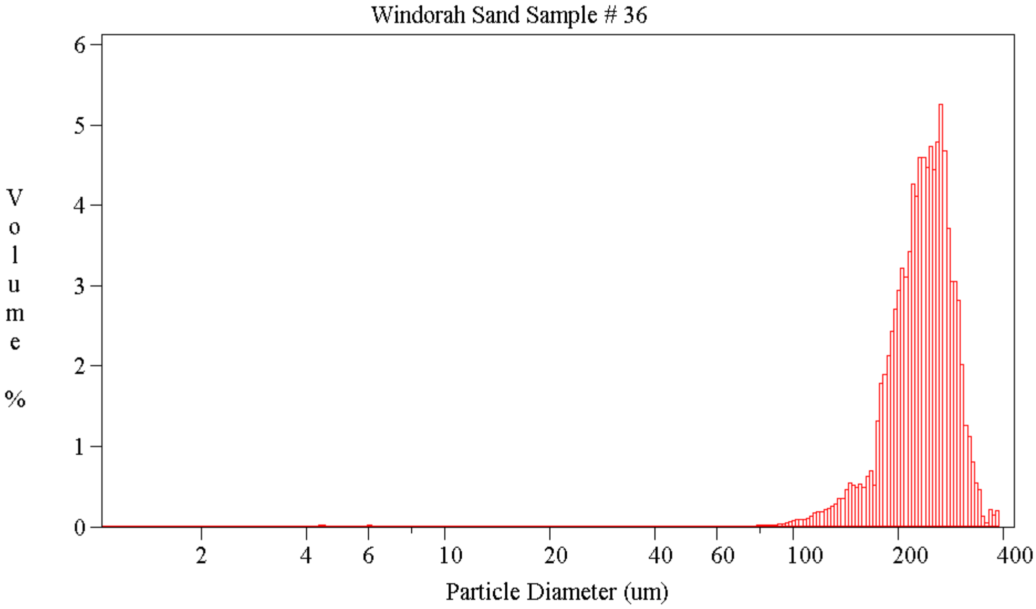
(t)


Simpson Desert Sample # 32
V o l u m e %
0
0.5
1
1.5
2
2.5
2
4
6
10
20
40
60
100
200
400
600
Particle Diameter (um)

(u)



(v)



Appendix A: (a) to (v) PSD's of sand dune samples.

Appendix B: Details of the sedimentological characteristics of 22 samples used in the study

Table B-1: Details of the 22 samples used in the study.

Sample ID	Mean [µm]	Standard Deviation [µm]	Redness Rating	Roundness (ρ scale) †	Sphericity ‡	Dust Yield [%]
1	180.0	43.8	0	3.66	0.71	0.54
2	187.0	40.6	0	3.84	0.75	0.49
3	141.8	39.9	0	3.78	0.73	0.50
6	152.9	45.8	3	3.82	0.73	0.70
7	194.6	115.0	0	3.58	0.73	0.80
9	240.8	109.0	2	4.06	0.74	0.76
10	165.7	46.4	3	3.86	0.73	0.73
13	188.8	52.8	7	3.48	0.75	0.55
14	141.3	37.9	7	3.28	0.76	0.41
18	166.6	54.1	8	3.68	0.71	0.68
19	142.8	50.8	8	3.80	0.75	0.50
20	159.9	53.9	12	3.82	0.73	0.67
21	231.5	104.0	8	3.70	0.73	0.61
23	211.7	59.7	8	3.74	0.72	0.46
25	179.6	46.9	6	3.50	0.70	0.64
26	172.0	56.2	7	3.58	0.75	0.66
27	228.8	75.7	5	3.57	0.75	0.47
28	198.1	49.9	3	3.76	0.77	0.56
30	309.5	105.0	15	3.96	0.73	0.87
32	262.8	124.0	8	3.90	0.72	0.98
35	248.7	145.0	3	3.10	0.77	0.80
36	232.8	53.8	12	4.20	0.78	0.75

†Wadell-Powers-Folk standard roundness images (McLane, 1995)

‡Zingg (1935) values: > 0.67 more spherical; <0.67 less spherical