Testing the auto-abrasion hypothesis for dust production using diatomite dune sediments from the Bodélé Depression in Chad

Charlie S. Bristow and Torsten H. Moller

Department of Earth and Planetary Sciences, Birkbeck College, University of London, Malet Street, London WC1E 7HX

Corresponding author: Charlie Bristow

e-mail c.bristow@mail.bbk.ac.uk

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ABSTRACT

This paper examines the role of quartz sand in the production of dust using mixtures of quartz sand from the Sahara and diatomite aggregates from the Bodélé Depression in Chad. An aeolian abrasion chamber is used to reproduce the physical processes of aeolian abrasion and test the hypothesis that the breakdown of saltating diatomite flakes as they collide in saltation, and with the surface, is the most prolific mechanism of dust production (auto-abrasion). This hypothesis is tested against the competing hypothesis that a hard, higher density quartz sand impactor is required to abrade fine-grained sediments to generate dust. The results show that dust can be produced by a mixture of saltating diatomite and quartz sand particles. However, quartz sand is not required for saltating aggregates to produce dust. Indeed these results, which used a mixture of very coarse-grained aggregate (1 to 2 mm diameter) with fine quartz sand, indicate that the addition of quartz sand can decrease dust production. For a very coarse aggregate (1 to 2 mm) a pure diatomite aggregate produced the most dust, although using a coarse-grained aggregate (0.5 to 1.0 mm) with a mixture of 20% quartz and 80% aggregate was found to produce the most dust overall. The results of this study confirm the auto-abrasion hypothesis for the breakdown of diatomite particles in the Bodélé Depression, which is the single biggest source of atmospheric mineral dust on Earth.

Keywords: Abrasion, aggregate, dust, Sahara, saltation, soil.

INTRODUCTION

The Bodélé Depression in Chad is acknowledged to be the most active dust source in the Sahara (Prospero et al. 2002) and the single biggest source of atmospheric mineral dust on Earth (Washington et al. 2003). Atmospheric mineral dust plays an important role in Earth's system. Within the atmosphere it can act as nuclei for ice crystals in clouds (DeMott et al., 2003), and it affects Earth's radiation budget either by absorbing thermal radiation or reflecting light (Highwood & Rider 2014, Miller et al. 2014). It is transported around the globe, and when washed out of the atmosphere or precipitated, it can affect many marine and terrestrial biogeochemical processes (Mahowald, 2011), including the carbon cycle (Jickells et al., 2014), the iron cycle (Mahowald et al., 2005) and the phosphate cycle (Okin et al., 2004; Mahowald et al., 2008). The Bodélé is particularly important because dust from the Bodélé is exported across the Atlantic Ocean as far as South America, taking with it nutrients that can fertilise the tropical Atlantic as well as the Amazon Basin (Koren et al., 2006; Ben-Ami et al., 2010; Bristow et al., 2010). The Bodélé is very remote and rarely visited but the BoDEx expedition to the Bodélé in 2005 provided unique field observations of a dust storm in the Bodélé (Washington & Todd, 2005; Washington et al., 2006), new ideas about the dust emission (Warren et al., 2007), measurements of dust flux (Todd et al., 2007; Chappell et al., 2008) rates of deflation (Bristow et al., 2009), and sample collection for dating (Armitage et al., 2015) and geochemistry (Bristow et al., 2010; Hudson-Edwards et al., 2014). During the BoDEx expedition Giles (2005) reported two scientists standing in the desert enjoying an argument about how the dust that becomes airborne was made. One subject of the argument was the relative importance of a quartz abrader in the production of mineral dust by saltation bombardment through sand blasting. Is it necessary to have quartz sand as an abrader? Or could the low density diatomite aggregate chips and flakes on the floor of the Bodélé Depression produce dust by themselves through a process termed auto-abrasion (Warren et al., 2007)? A working definition of auto-abrasion is the fracture or fragmentation of aggregate particles as a result of collisions between aggregate particles in transport, as well as collisions between aggregate particles and the surface. In an attempt to answer that question experiments have been conducted in an abrasion chamber using samples of sand-sized aggregate from dunes in the Bodélé mixed with various proportions of aeolian quartz sand to test the auto-abrasion hypothesis.

Dust aerosols are emitted by three distinct processes: (i) direct aerodynamic lifting; (ii) saltation impact bombardment; and (iii) disintegration of soil aggregates involved in saltation (Shao, 2001, 2008). The direct lifting of aerosols is limited by the binding forces between fine-grained particles (Greeley & Iverson, 1985), leaving saltation bombardment and aggregate disintegration as the two most important mechanisms for generating dust. Both modelling and field studies have highlighted the importance of saltation for large-scale dust emission (Shao et al., 1993; Lu & Shao, 1999; Shao, 2001; Sow et al., 2009; Parajuli et al., 2015). Within the context of the Bodélé Depression these two mechanisms can potentially be distinguished due to a contrast between the mineralogy of the impactor and the aggregates. In the Bodélé the impactor is quartz sand blown into the depression from upwind and locally sourced from quartz-rich fluvial and aeolian sediments. In contrast, the substrate and aggregates are commonly composed of diatomite sediments that are locally derived and have a distinct colour, size and density. The difference in density, colour and size enables the two types of sediment to be separated and then reconstituted in a controlled experiment.

This paper reports the results of a simple experiment to test the role of a quartz sand abrader on dust production using an abrasion chamber. The quartz sand is fine-grained aeolian sand from the Grand Erg Occidental in Algeria and the aggregate is coarse and very coarse grained diatomite particles from a grey diatomite dune in the Bodélé Depression, Chad.

SURFACE SEDIMENTS IN THE BODÉLÉ

The Bodélé Depression lies within northern Chad, on the southern margin of the Sahara Desert. Around 6000 years ago it was filled by a vast freshwater lake, palaeolake Mega-Chad that was up to 60 m deep (Schuster 2005, Drake & Bristow 2006). Since then the waters in the lake have evaporated leaving behind a layer of sediment locally more than 2 m thick that is very rich in the organisms that used to live within the lake, primarily diatoms, but occasional fish remains along with detrital clays that were washed or blown into the lake. Now that the lake has dried out the lake bed sediments are desiccated and exposed to wind erosion (Bristow et al., 2009). Because diatoms are abundant in the palaeolake sediments the sediments are called diatomite. The diatomite and diatomaceous sediments cover an area of 24,000 km^2 (Bristow et al., 2009). Since it dried out the diatomite has cracked, probably due to shrinkage, producing desiccation cracks (Fig. 1A). In addition, the surface is breaking up into centimetre-sized chips, either due to occasional wetting and drying or more likely thermal expansion and contraction, leaving the surface covered in loose centimetre-sized particles (Fig. 1A). The diatomite has a density of around 0.8 g/cm^3 because the diatom frustules are hollow tubes (Fig. 1B). Due to the low density of the diatomite particles up to 2 cm diameter can be entrained by the wind and moved as saltation load (Warren et al., 2007, and field observations). Quartz sand deposits are available from fluvial sediments that underlie the diatomite. In addition, quartz sand is transported into the Bodélé Depression from upwind. This quartz sand can act as an abrader, eroding the *in situ* sediments by sand blasting. In addition, the diatomite aggregate particles are eroded and reduced in size due to fracturing and abrasion during transport. Mobile aggregates of quartz sand and diatomite particles form dunes, granule ripples, and ripple bedforms on the surface of the former lake bed (Fig. 1C and D).

SAMPLES

The materials used in this experiment were collected from active dunes and are thus part of the saltation load. The quartz sand sample PV2 is a fine-grained quartz-rich aeolian sand from the Grand Erg Occidental in Algeria (30^{o} 35’ 31.0” N 02^{o} 06’ 04.2” E). The aggregate (CH 56) was collected from a grey diatomite dune in the Bodélé Depression in Chad (16^{o} 51’ 51.3” N, 17^{o} 38’ 21.7” E). Both samples were sieved to remove any existing very fine sand, silt or loose clay-sized fraction. The quartz sand sample was sieved using 250 µm and 125 µm sieves to extract the fine sand fraction. Grain coatings on the quartz sand were removed by boiling in concentrated hydrochloric acid for ten minutes before rinsing in distilled water, followed by boiling in stannous chloride solution for 20 minutes before being rewashed and rinsed in distilled water following the method of Krinsley & Doornkamp (1973). This produced clean fine-grained quartz sand with no grain coatings (Fig. 2A). The diatomite aggregate was sieved using 2000 µm, 1000 µm and 500 µm sieves to produce a very coarse-grained sample (1000 to 2000 µm) and a coarse-grained sample (1000 to 500 µm) (Fig. 2B and C). Dry sieving preserves the soil fabric and avoids the breakage of soil aggregates (Alfaro & Gomez, 2001; Laurent et al., 2006). The very coarse particles (2000 to 1000 µm) are all aggregate, the coarse particles (1000 to 500 µm) are diatomite aggregate with rare quartz grains (Fig. 2B and C).

METHOD

This study used an abrasion chamber based upon the designs of Whalley et al. (1982), Wright et al. (1998), Bullard et al. (2004, 2007) modified with the addition of a second electrostatic dust trap (Fig. 3) because in tests it was found that dust was passing through the exhaust tube and trapping efficiency was less than previously reported. Air flow in the apparatus was set to 28 litres per minute, close to the 0.0279 m^3min^{-1} used by Bullard et al. (2004, 2007) for 72 hours. The 72 hour duration of the experiment was determined by Bullard et al. (2004, 2007) because dust production from Australian dune sands was initially high but declined after 48 hours. The present authors have no evidence that the Bodélé samples will behave in a similar manner but used the same duration so that the results could be compared directly with those of Bullard et al. (2007). The airflow was sufficient to raise fine sand to elevations of around 10 cm within the test tube, although coarser sands showed less movement. Dust produced was collected on an electrostatic precipitator operating at 5 kV. The laboratory was climate-controlled at a temperature of 20° ± 1°C, and a relative humidity of 50 to 60%. At the end of each run the brass rods and brass tubes that comprise the electrostatic dust traps were washed with distilled water. The water was then filtered through a pre-weighed Whatman® 0.45 micron nylon membrane filter. The filters were placed in a drying oven for 24 hours and weighed again after drying. The difference in mass of the filter before and after is considered to be the mass of dust produced in the experiment. The experiments were repeated twice using different size fractions of the diatomite aggregate in each set of experiments.

RESULTS

Within the abrasion chamber the airflow was sufficient to entrain fine sand and raise it to elevations of around 10 cm within the test tube, although coarser sands showed less movement and were lifted only 1 to 2 cm. Sand particles interacted in several ways: some entrained particles impacted the bed setting other particles in motion, some particles collided with other saltating grains, some collided with the chamber walls, others rolled and occasionally avalanched at the base of the chamber, simulating a range of natural sand transporting processes and particle interactions. The results of the experiment are shown in Table 1 and Fig. 4. The results of the two sets of experiments show a positive relationship between the amount of dust produced and the percentage of diatomite aggregate in each run, with the very coarse aggregate producing less dust than the coarse aggregate with equivalent quartz percentage. It is notable that the finer grained (500 to 1000 µm) aggregate produced twice as much dust as the coarser grained aggregate.

DISCUSSION

The replicability of the method was tested by Bullard et al. (2004) who found that results varied by a factor of two (0.0171 to 0.0308 g). Repeating the present experiments with sample CH56 (unsieved) produced values of 0.0119 g, 0.01607 g, and 0.02018 g showing a similar range of values. As noted by Bullard et al (2004) some of the variability can be attributed to small sample size where fracturing and fragmentation of a small number of grains will have a large impact on the total mass of dust produced. The electrostatic dust trap was described by Whalley et al. (1987) as having an estimated efficiency greater than 95%. In the light of trials where dust was observed in the tube from the exhaust outlet the present authors doubted this assertion and added a second electrostatic dust trap in series (Fig. 3). When comparing results from the two electrostatic dust traps, similar amounts of dust were found in each trap suggesting that the trapping efficiency might be closer to 50%. The efficiency of the electrostatic dust trap is potentially a large source of error resulting in an underestimate of the dust produced. There are other potential losses within the apparatus. Small amounts of dust adhere to the glassware, and the washing of the brass electrodes is not completely effective and leaves some dust behind. This is known because after washing with distilled water the brass ware was wiped dry with a clean dry tissue and the tissue often showed a stain of dust. Aeolian abrasion can produce sub-micron sized particles (Baddock et al., 2013) and it is possible that some sub-micron sized particles have passed through the 0.45 µm filter, although the mass is likely to be very small. The amount of dust lost in each run has not been quantified. However, it is apparent that the amount of dust recovered in each run is less than the amount of dust produced, therefore the errors are all in the same vector and probably a similar magnitude.

In the experiments conducted by Bullard et al. (2007), using dune sands from Australia, the majority of the dust produced by aeolian abrasion was from the removal of clay coatings on the grain surface. In this set of experiments, the quartz sand was boiled in concentrated hydrochloric acid, stannous chloride solution to remove clay coatings and iron oxides prior to conducting the experiments. This treatment effectively reduced the amount of dust that might have been produced by the quartz grains in their natural state by removing clay coatings. Consequently, grain coatings on quartz grains are not included in the following conceptual model because they were removed for the experiments.

The results show a trend for dust production to increase with the percentage of diatomite aggregate (Fig. 4). The very coarse aggregate produced less dust than the coarse aggregate with equivalent mixtures of quartz and aggregate. The greatest amount of dust was produced by a mixture of 20% quartz with 80% coarse-grained aggregate (Table 1; Fig. 4). For the very coarse-grained aggregate the amount of dust from the 80% aggregate 20% quartz sand mix was exceeded by the dust produced by aggregate alone (Table 1; Fig. 4). The observation that the aggregate alone produced the most dust in one set of experiments and second highest amount of dust in the second set of experiments confirms the hypothesis of Warren et al. (2007) that the breakdown of saltating diatomite particles as they collide in saltation (Dong et al., 2006), and with the surface, is a prolific mechanism for dust production, at least for the Bodélé diatomite aggregates.

The results tend to support the formation of dust particles through the fracturing and fragmentation of dust aggregates (Kun & Herrmann, 1999; Kok, 2011) as the transfer of kinetic energy into aggregates is sufficient to break the bonds between the constituents of the aggregate (Alfaro et al., 1998; Alfaro & Gomes, 2001). This process creates dust aerosols either by damaging, or fragmenting the aggregate, breaking it into a large number of fragments (Kok et al., 2012). In contrast, the quartz sand is relatively hard, has stronger chemical bonds and is less likely to fracture. Thus quartz – quartz collisions produce little damage and little dust.

The results do not show a linear relationship between the percentage of diatomite and the amount of dust produced. It is hypothesized here that this can be best explained by considering the ratios of the grain interactions: quartz – quartz, quartz – aggregate and aggregate – aggregate (Fig. 5). When there is only quartz sand in the abrasion chamber all of the collisions must be interactions between quartz to quartz, and quartz to the chamber walls. Quartz – quartz collisions produce little dust due to the strong chemical bonds within quartz molecules. When there is only aggregate in the abrasion chamber all collisions must involve aggregate grains resulting in more fracturing and fragmentation and increased dust production, and at least for the very coarse aggregate, the most dust. However, within a mixture of quartz sand and aggregate some collisions will be quartz to quartz, some quartz to aggregate, and some aggregate to aggregate (Fig. 5). The amount of dust produced appears to be a function of the collisions that include aggregate grains. Thus, the total amount of dust produced is a combination of quartz – aggregate, and aggregate – aggregate collisions (Fig. 5).

Comparison with other dune sands

In their study of dust production from Australian dune sands Bullard et al. (2007) found that abrading red desert dune sands for 72 hours produced 0.6% dust by mass (n = 22). The present work used a similar experimental method to Bullard et al. (2007) so that the results should be comparable but show maximum values of 0.25%. The Bodélé dune aggregate grains produce less dust than Australian dune sands. This is a surprising result because the Bodélé is such a prolific dust source and in most papers on the Bodélé the efficacy of the dust source is in part attributed to the physical characteristics of the diatomite sediments as well as the frequent high velocity winds. However, it should be noted that the samples used here are relatively coarse-grained aggregates, which did not saltate strongly in the abrasion chamber. The Australian dune sands have a mean grain size of 149.5 µm (n = 22). Reducing the grain size of the aggregates doubled the dust production and further reductions in grain size are predicted to increase dust production even more. Increasing the airflow in the abrasion chamber would probably increase the particle interactions and the dust production. Experiments with finer grained aggregates under similar conditions have produced an order of magnitude more dust (Bristow & Moller, in prep). The reduction in dust production with increased grain size can be attributed to two factors: within 10 g of sample there are less very coarse particles than there are in 10 g of coarse particles, in addition, the larger grains are more difficult to entrain. As a consequence, with the smaller particles there are more grains active, and more collisions between particles, resulting in increased dust. The present authors speculate that finer grained aggregate, and an increased airflow, simulating stronger winds, will produce more dust.

These results provide strong evidence to support the auto-abrasion hypothesis where saltating diatomite particles break down as they collide in saltation with other aggregates, as well as the surface, suggesting that this is the most prolific mechanism of dust production for aggregates in the Bodélé Depression; they do not preclude the role of a quartz abrader in sand blasting the *in situ* diatomite deposits of the Bodélé Depression. Field evidence from erosion features suggests that sand-blasting of diatomite surface sediments in the Bodélé does occur (Bristow et al., 2009; Chappell et al., 2008; Warren et al., 2007).

CONCLUSIONS

The results of these experiments confirm the auto-abrasion hypothesis that the breakdown of saltating diatomite aggregate particles as they collide in saltation and with the surface is a prolific mechanism of dust production. The experiments demonstrate that a quartz abrader is not essential for dust production. Saltating aggregate grains can produce dust by themselves without the addition of quartz. Indeed, the addition of a fine quartz sand abrader to a very coarse-grained aggregate appears to decrease dust production, at least within these samples from the Bodélé. It is hypothesized here that this could be due to a percentage of the grain interactions being quartz to quartz, and quartz to the chamber walls rather than quartz to aggregate. Quartz to quartz collisions produce little dust due to the strong chemical bonds within quartz molecules. When there is only aggregate in saltation all collisions must involve aggregate grains resulting in more fracturing and fragmentation and increased dust production. Within a mixture of quartz sand and aggregate some collisions will be quartz to quartz, some quartz to aggregate, and some aggregate to aggregate. The amount of dust produced appears to be a function of the collisions that include aggregate particles.

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TABLES

Mixture sand /aggregate	Diatomite aggregate size fraction	
	1000 to 2000 µm	500 to 1000 µm
100% quartz sand	0.57	-
80% quartz, 20% aggregate	7.58	8.05
60% quartz, 40% aggregate	10.14	21.1
40% quartz, 60% aggregate	10.85	22.5
20% quartz, 80% aggregate	11.37	25.56
100% aggregate	12.92	23.35

Table 1. Results of the abrasion experiments with the mass of dust produced in milligrams.

FIGURE CAPTIONS

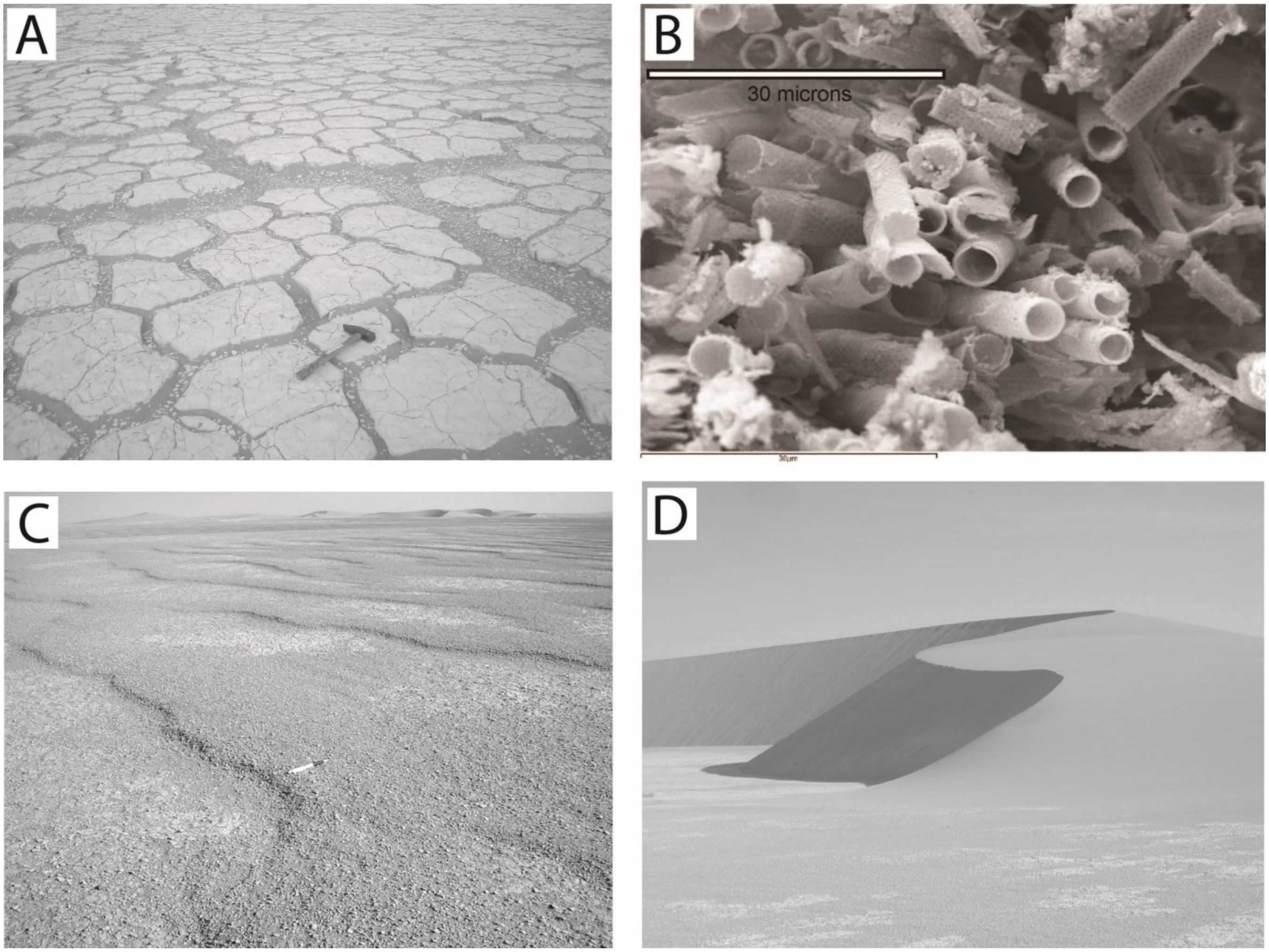

Figure 1

Sediments from the Bodélé Depression. (A) Pale grey diatomite lake bed sediments with cracks most likely formed during desiccation. The cracks are filled with sand and centimeter-sized diatomite clasts, geological hammer for scale is 37 cm in length. (B) Scanning electron microscopy (SEM) image of diatomite sample CH showing hollow tubes (frustules) from fresh water diatoms *Aulacoseira* spp. 30 µm scale bar. (C) Granule ripples are widespread on the former lake bed and include granule-sized grains of quartz sand and centimetre-sized diatomite particles that are classed as pebbles on the Uddon–Wentworth scale (Wentworth 1922), pen for scale is 13 cm in length. (D) Grey-coloured sand dunes within the Bodélé are composed of particles of diatomite eroded from the desiccated lake bed and transported by saltation.

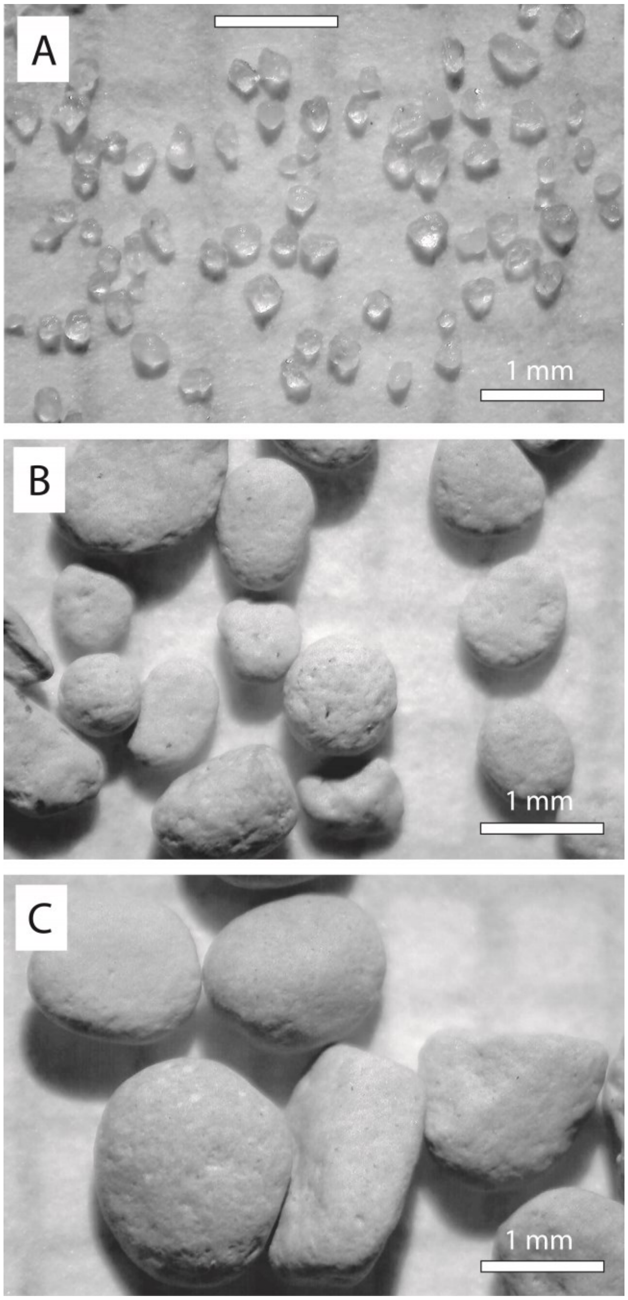

Figure 2

Photomicrographs of the samples used in these experiments. (A) Acid washed and sieved fine-grained sand PV2 (field of view 5 mm). (B) Sieved sample of CH 56 500 to 1000 µm (field of view 5 mm). Sieved samples of CH 56 1000 to 2000 µm (field of view 5 mm). Note that the diatomite aggregate particles are well-rounded grains from a dune.

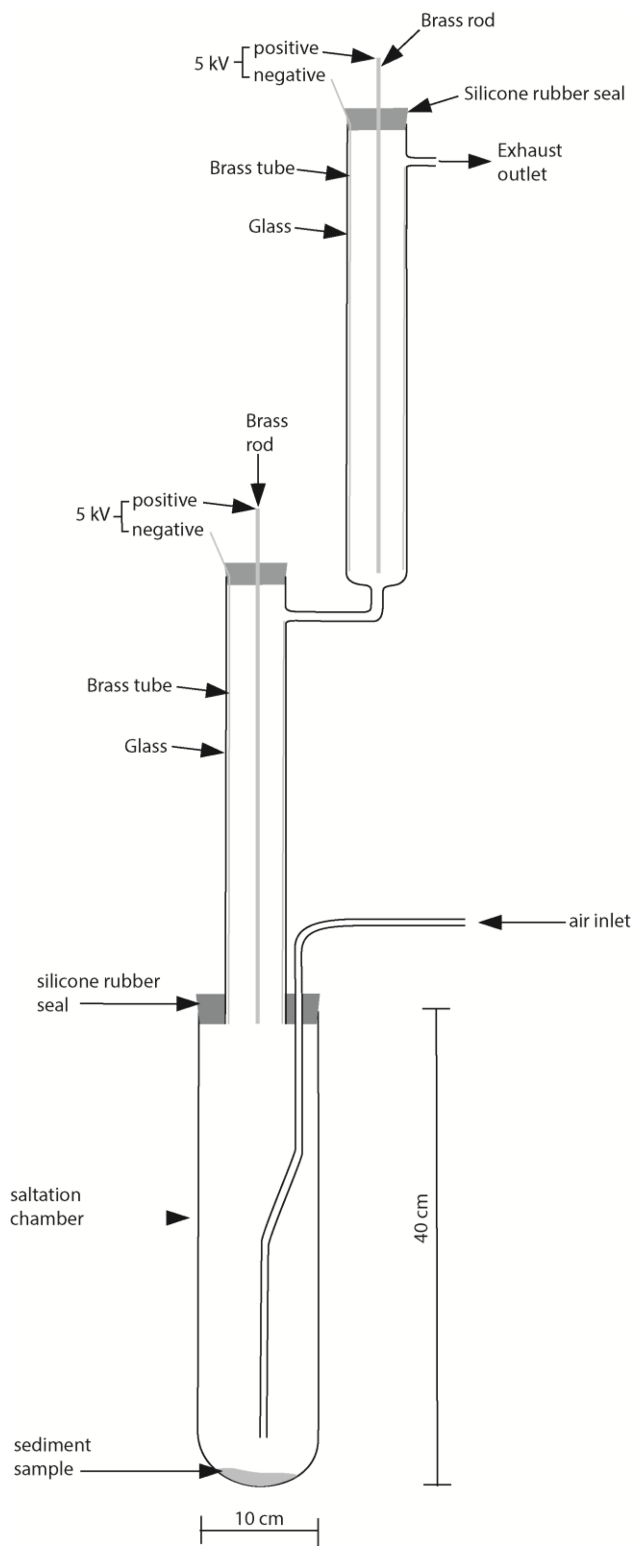

Figure 3

Schematic diagram of abrasion apparatus used in these experiments.

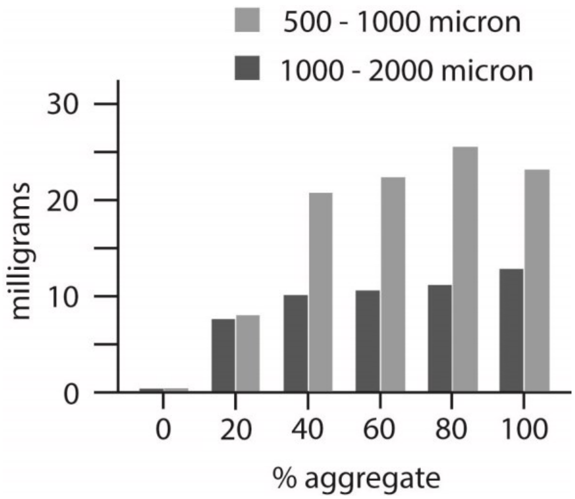

Figure 4

Histogram of results. The amount of dust increases with an increase in the percentage of aggregate grains for both size fractions. The coarse particles (500 to 1000 µm) produce more dust than the very coarse particles (1000 to 2000 µm). The greatest amount of dust was produced with a mixture of 20% quartz sand and 80% aggregate particles.

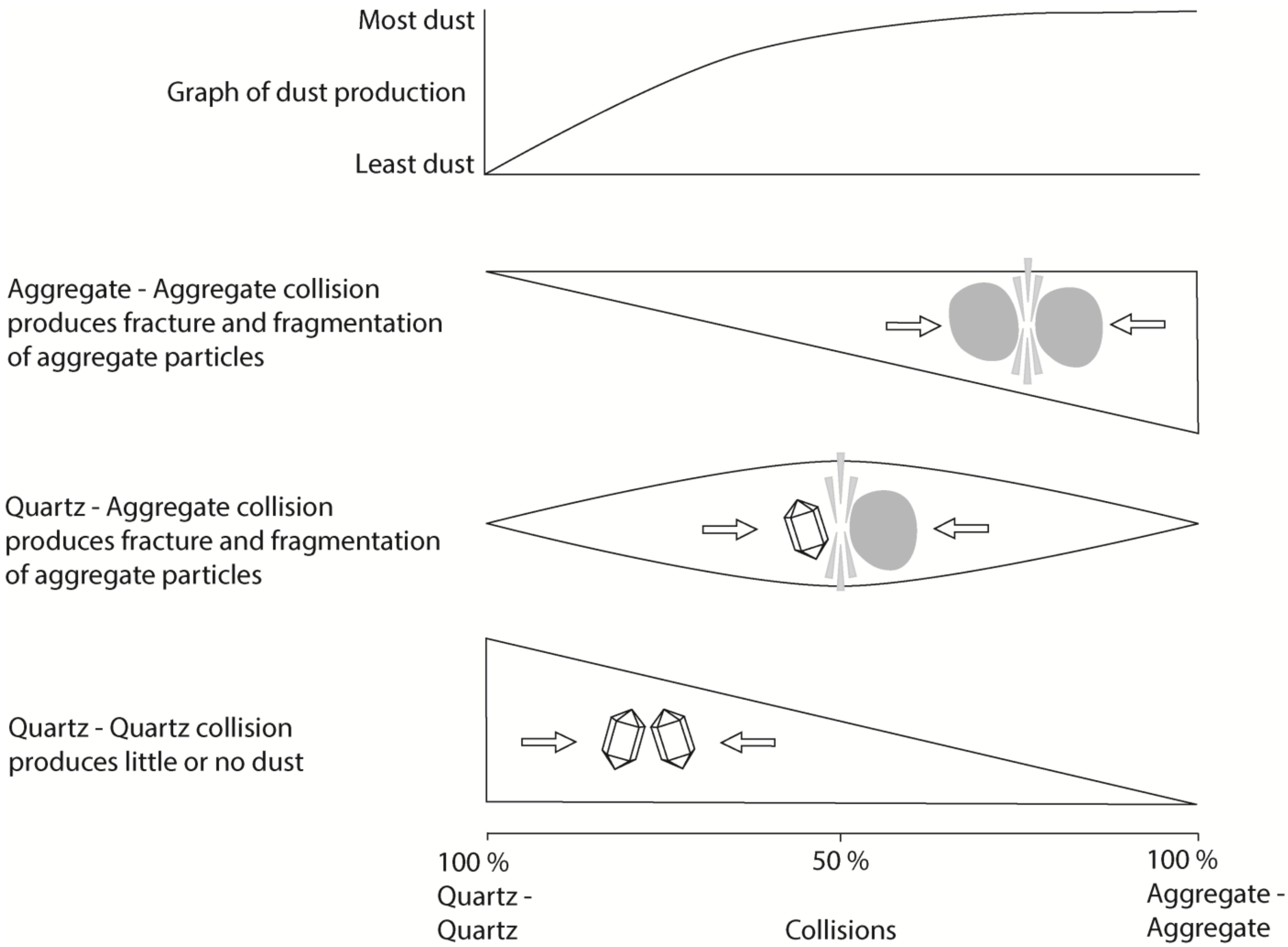

Figure 5.

Hypothetical model of particle interactions and dust production. Quartz – quartz collisions produce little dust due to the strong chemical bonds within quartz molecules. When there is only aggregate in saltation all collisions must involve aggregate grains, resulting in more fracturing and fragmentation and increased dust production. Within a mixture of quartz sand and aggregate some collisions will be quartz to quartz, some quartz to aggregate, and some aggregate to aggregate. The amount of dust produced appears to be a function of the collisions that include aggregate grains, which is a combination of the quartz to aggregate as well as the aggregate to aggregate collisions.