Gaps in Particulate Matters: Formation, Mechanisms, Implications

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ABSTRACT: Ageing of soil may induce an unwelcomed degree of spatial variability in soil parameters. Ageing is influenced by fatigue in soil's frame elements (quartz constituents) and cause particle size diminution, shape alteration or crystalline damage. There are substantial literature trails on mechanisms of particle splitting, yet neither a universal quartz comminution model nor an explanation for the fractal features of size diminution exists. The universal shortage of certain size particles has received little attention and the probable links between particles' shape and chance to survive in the terrestrial system is very improperly understood. This work seeks a better understanding of the controls on the universal particle size deficiencies, and implications on soil ageing in the near-surface environment. Four Peridesert, Perimountain, and Periglacial sands collected from Northern and Southern hemisphere are mechanically crushed into a range of grades. Particle size histograms are studied in conjunction with particle shape data within the context of three fundamental questions: Are there any universal size ranges at which particles fail to survive in the natural/engineered environment? Is there a link between particle size gaps and particles' origin? Is there a link between gaps and particle shape?

1 INTRODUCTION

Size diminution of quartz geomaterials as a result of natural erosive or manmade transient low-order loading is referred to as 'fatigue fracturing' in the geotechnical literature. The role of fatigue in the erosive environment continues to be debatable: Effectiveness of fatigue is argued in Rittinger (1867), Bond (1952), and Wright & Smith (1993) but has received support in Moss (1973), Rabinowicz (1976), and Sharp & Gomez (1986). More recently, Assadi-Langroudi et al. (2014) reported on their studies on clastic periglacial Leighton Buzzard English sand and presented experimental evidence to support fatigue fracturing as one form of ageing that is common in clastic quartz detrital materials. They discussed the fractal features of quartz sand breakage and proposed two sequent size diminution mechanisms: particle crystalline breakage and fatigue fracturing. The two modes (i.e. ageing mechanisms) generally tie in with the existing knowledge across the sedimentary and quaternary sciences disciplines.

In his seminal work, Pye (1995) proposed eight mechanisms for generation of earth's silt stock, covering a range of mechanical, chemical and biological weathering systems. On that basis, he then categorized the terrestrial silt into three main Periglacial, Peridesert, and Perimountain types. The emphasis of the majority of existing research however strictly ends to be on clastic periglacial quartz. Periglacial quartz sand and silt are product of glacial grinding of granitic (or other rocks such as shale) rock beds in glaciers and is widely accepted as the main type of present-day terrestrial silt stock (Smalley et al. 2006). This contribution will test the current perception within the context of ageing and seeks a universal ageing mechanism valid for all three main types of quartz sand. The pronounced and missing particle mode sizes will be used as two proxy parameters in this work to first compare the implications of breakage in the three main quartz sand families, and then to seek (and test the existence of) yet-unexplained universally favoured and unfavoured particle sizes.

2 QUARTZ REDUCTION

2.1 *Mechanisms*

Quartz appears in nature in form of clastic and mature (i.e. with intact crystalline structure) particulate matters. Both types form as siliceous magma solidifies into plutonic rocks. Initially, β-Quartz (i.e. high quartz) minerals form. As temperature drops, structural and molecular changes transforms 'high quartz' into the denser 'low quartz'. The transition is displacing, in Oxygen bonds re-orienting to contract the quartz crystals and generate tensile stresses. The transition also involves in formation of Eutectic features, representing taxonomic diversity across quartz. These features appear in form of explicit colour and crystalline variations under light transmitting microscope. In clastic quartz, the eutectic features generate sets of internal planes of imperfection, cleavages or weakness planes, along which particles split to smaller sizes upon impact or prolonged stressing (i.e. fatigue). In mature quartz however, micro-cracks are more likely to appear around eutectic features in form of impact induced chatter marks. The two breakage mechanisms conspire the comminution (i.e. size reduction). Impact induced chatter marks gradually expand to conchoidal fractures, representing larger wedge failures close to particle edges. Greater orders of stress at particle edges leads to edge chipping and delivery of angular fine silt. Through the size reduction process, particles of certain size survive to form pronounced modes (i.e. favoured sizes). A cohort of particles of certain size fail to resist the erosive environment, generating gaps in size distribution data which here are termed unfavoured sizes.

2.2 *Favoured and Unfavoured Sizes*

Early studies on fresh weathered rocks by Blatt (1967) suggested a pronounce mode size of 600 to 670 μm for crystalline rocks, 720 μm for Gneisses and massive plutonic rocks, and 440 μm for Schist rocks across South California and Arizona. Blatt (1970) showed that more than 90% of the most 600-700 μm sands (from crystalline rocks) continue to break to silt (60 μm). Jefferson et al. (1997) simulated the reduction of defected quartz sand in a glacial abrasive environment to refine the silt mode size to 20-30 μm. The 20μm mode was reported in the earlier Smith et al. (1991) work on aeolian abrasion of Pannonian sand. They showed the formation of 20-40μm and 60μm modes upon prolong stressing. This is a pivotal work that was later verified in Wright et al. (1998) for mature Peridesert crystalline intact quartz and Kumar et al. (2006) for defected Perglacial quartz.

The quartz particle literature, especially silt-sized quartz, is shared with the Loess literature on the tenets of aeolian silt being the predominant component of loess soils. Within the loess context, favoured silt size ranges from 20 to 50μm (Smith et al. 2002). Recently, Assadi-Langroudi (2019) gave a thorough review of formation, distribution and characteristics of Periglacial silt across the UK. Silt size measurements reported in this work are closely consistent with loessic silt ranges reported in literature. A few investigators have noted the typical shortage of particles across the sand and gravel range of quartz clasts: Tanner (1958) suggested a universal shortage of 120μm-1mm and 1mm-8mm sand grains. Yastsu (1966) moderated the gravel side of gap to sediments in the 2-4mm (and 8-10mm) range. The particle shortage in sedimentary system on the silt side has never been explored.

2.3 *Dilemma and Significance*

Within the tenets of the quaternary science, quartz particulate matter is predominantly product of glacial abrasion. This viewpoint contests the existence of a universal quartz comminution mechanism that works independent from the crystalline integrity of detrital quartz, so too existence of any probable universally favoured and unfavoured particle diameters.

Assadi-Langroudi et al. (2014) showed that the quartz sand to silt transition is not necessarily an energy dependent process, but quartz breakage is likely to be limited to inherently breakable quartz sand, where splitting occurs along sets of internal planes of imperfection (i.e. internal defects). They presented microscopic signatures of internal defects and linked these with contraction of quartz crystals during its formation and especially the high to low quartz transition. They presented a fractal framework for quartz size reduction to show certain particle size fractions receive high particle population along the fragmentation and linked this favoured fraction to internal defects. In their work, fractal properties were restricted to Periglacial sands in compliance with previous often contradictory published findings. Restricting the fractal features of terrestrial quartz particulate matters to defected Periglacial sands continues to be a matter of debate. Better understanding of these 'ageing' procedures informs and benefits a range of disciplines including geomorphology and sedimentology, material and planetary sciences.

3 MATERIALS AND METHODS

3.1 *Testing material*

Four base sands are studied: Peridesert mature silica sand collected from Western Cape South Africa (WCS), Perimountain Craig Rofft quartz sand collected from Llandudno North Wales (CRS) and two fine and medium grades of standard English Periglacial Lower Greensand Leighton Buzzard sand (LBF and LBM). Table 1 demonstrates the physical properties of the testing materials. The WCS has a unimodal size distribution and is a well sorted symmetrical platykurtic slightly very fine gravelly very coarse sub-angular sand type. The WCS sand was crushed using an end-runner mill that simulates the low-energy random clast to particle and particle to particle impact environment. The CRS has a trimodal size distribution and is a very poorly sorted fine skewed leptokurtic very coarse silty fine sub-angular sand type. A low energy disc mill was used to simulate the frost shattering erosive forces and to crush base sand into finer grades. The LBF has a unimodal size distribution and is very well sorted medium symmetrical skewed platykurtic sub-rounded sand type. The LBM has a uni-modal size distribution and is very well sorted very coarse symmetrical skewed leptokurtic sub-rounded sand type. A high-energy Siebtechnik disc mill was used to simulate glacial grinding through combined abrasion between grains' asperity tips, and between particles and rotating smooth tungsten carbide pestle.

3.2 *Methods*

Prior to physical characterisations, samples were air-dried and crumbled using a plastic mortar. In Table 1 and using the geometric Folk and Ward method, $\bar{x}_G$ is the mean particle size, σ_G is the standard deviation or sorting, Sk_G is the skewness, and K_G is the Kurtois index. Equations 1 to 4 formulates the latter four in relevance with P_i, the particle diameter in µm at the cumulative percentile value of i.

Table 1. Base sand properties

	LBF	CRS	LBM	WCS
Particle size distribution				
Mode 1: µm	500.0	206.0	1015.0	1250.0
Mode 2: µm	-	550.0	-	-
Mode 3: µm	-	61.50	-	-
D_{10}: µm	412.1	13.67	824.3	936.6
D_{50}: µm	488.9	121.3	1003.0	1338.2
D_{90}: µm	579.9	554.1	1229.4	1862.7
C_u	1.64	22.34	1.32	1.22
C_g	0.82	0.98	0.97	1.03
$\bar{x}_G$: µm	488.9	110.6	1003.0	1343.6
σ	1.140	4.344	1.241	1.302
Sk	0.000	-0.19	-0.03	-0.04
K	0.738	1.239	1.889	0.860
Pore size distribution				
Mode 1: µm	115.5	10.54	311.3	-
Median: µm	115.5	18.51	291.2	-
Mean: µm	115.5	17.18	291.2	-
Packing density thresholds				
e_{min}	0.525	0.617	0.498	-
e_{max}	0.842	1.024	0.769	-
G_s	2.65	2.65	2.62	2.68
Shape and texture				
R	0.33	0.56	0.35	0.28
S	0.65	0.68	0.81	0.63
ρ	0.49	0.62	0.58	0.45

$$\bar{x}_G = exp\left(\frac{lnP_{16} + lnP_{50} + lnP_{84}}{3}\right) \quad (1)$$

$$\sigma_G = exp\left(\frac{lnP_{16} - lnP_{84}}{4} + \frac{lnP_5 - lnP_{95}}{6.6}\right) \quad (2)$$

$$Sk_G = \frac{lnP_{16} + lnP_{84} - 2lnP_{50}}{2(lnP_{84} - lnP_{16})} + \frac{lnP_5 + lnP_{95} - 2lnP_{50}}{2(lnP_{95} - lnP_5)} \quad (3)$$

$$K_G = \frac{lnP_5 - lnP_{95}}{2.44(lnP_{25} - lnP_{75})} \quad (4)$$

BS1377 compliant methods for sieving was adopted to determine the size distribution of coarse fragments. Gravity Sedimentation was adopted to determine the sub-63µm size distribution. Standard Calgon solution (33g Sodium Hexametaphosphate and 7g Sodium Carbonate in 1L of distilled water) was used to facilitate dispersion. Sieving-sedimentation datapoints were numerically fitted, using non-linear regression and the Levenberg-Marquardt algorithm. Fitted data was then used to determine the pore size distribution for openly-packed assemblages of 600 cubic packing (e=0.9, Pd=0.52), employing the Arya-Paris pedo-transfer function PTF (Arya and Paris 1981).

Transmitting light microscopy was adopted to determine particles' shape and texture: Grains were treated with 0.5N HCl solution (150ml acid diluted with distilled water into a total volume of 800mL) to remove Carbonates. Treated grains were then thoroughly washed with distilled water and treated with a 35% by mass H_2O_2 solution to remove the organic matters. Treated grains were washed with distilled water and dried at 40°C for 24 hours before microscopy analysis. An UB200i Lacet transmitting light microscope (integrated with DCM-900 digital camera) was used to capture the particle's shape and texture data. Particle shape was determined, for a randomly picked subset of particles, using equations 5 to 7. Particle shape is described here in terms of sphericity, roundness, and smoothness. Sphericity (S) is a measure of convergence of particle dimensions in the 3D coordinate system. Particles with highest sphericity contain minimum eccentricity and platiness. Roundness (R) is a measure of surface features scale relative to the radius of the particle. Angular particles gain the minimum roundness index. Sphericity and Roundness often appear, in particulate physics, in a single 'particle regularity' (ρ) parameter.

$$S = \frac{r_{max-in}}{r_{min-cir}} \quad (5)$$

$$R = \frac{\sum \frac{r_i}{N}}{r_{max-in}} \quad (6)$$

$$\rho = \frac{R + S}{2} \quad (7)$$

where, r_{max-in} is the radius of the largest sphere inscribing the particle, $r_{min-cir}$ is the radius of the smallest sphere circumscribing the particle, and r_i is the equivalent average radius of surficial features. Minimum and maximum void ratio was determined in compliance with ASTM D4254-00.

4 RESULTS AND DISCUSSION

4.1 *Universal Comminution Mechanism*

Figure 1a-d presents the distribution of pronounced and less-pronounced mode sizes for four testing sands. Favoured and unfavoured mode sizes are presented in green and red bars, respectively.

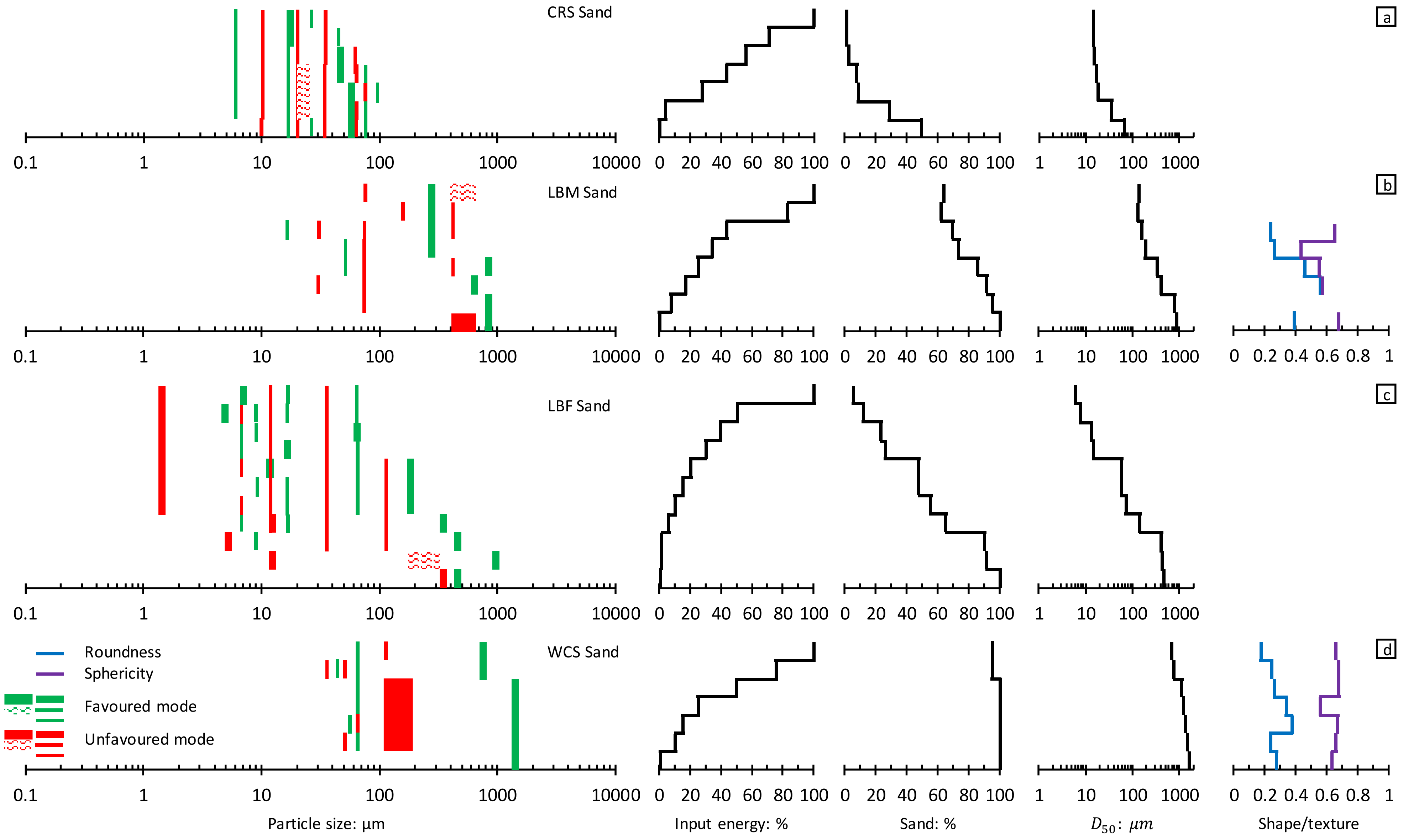

Figure 1. Comminution data: Input energy, Favoured and unfavoured size, Median size, Sand content, and Shape [a] CRS Sand, [b] LBM Sand, [c] LBF Sand, [d] WCS Sand

Upon application of input energies <5% of maximum effort to defected Periglacial and mature Peridesert sands, and despite the loss of 4-10% of sand fraction, the median size just marginally dropped, and sand retained its main favoured mode. Largest loss in sand content was detected in the relatively finer LBF under the low 2% input energy. This led to an increase in the main favoured mode to nearly 1mm, close to the main favoured mode in LBM and WCS sands. It appears that fragmentation begins at sands' fine fraction. Larger particles function as clasts, splitting the fines into the silt fragment. Where the silt output forms large volumes, the powdered silts coagulated to form peds of 800-1000μm in size. The latter appears to be one universally favoured size for sand.

The test data suggests that along the comminution process, clusters of same-sized particles break into finer fragments, whereby favoured modes change to unfavoured modes and new favoured modes form at finer size ranges. The favoured and unfavoured modes alternate: Common modes receive and lose particle population as favoured and unfavoured modes alternate. For periglacial sand, common modes include 5, 7, 12, 316 and 610μm. A single 68μm was captured in peridesert sand. For perimountain sand, 20 and 75μm modes were common between favoured and unfavoured modes. There does not appear to be any universal common mode. Existence of common modes however suggests that crushability of sand is not necessarily a factor of magnitude of energy. Survived particles may still break under prolonged application of small energies and upon formation of fresh internal imperfections. Transition of main favoured mode from 1414μm to 774μm upon an increase in impact effort from 50% to 75% in the WCS sand is an example of breakage upon prolonged loading (i.e. here 0 to 50% level). This form of breakage is broadly known as fatigue fracturing. Fatigue fracturing is an ageing phenomenon common to sands of any origin but is most marked in mature Peridesert sands. This contradicts some previous findings (Wright, 1995).

Following an initial phase of breakage across the fine fragment whilst the silt fraction is less than 7 to 10%, median size begins to reduce. Larger sand particles begin to split along internal cleavage planes. As the silt fraction increase to orders as high as 50%, sand grains enjoy enhanced levels of coordinate number and gain a higher chance to survive. Breakage continues in the fine fragment. Figure 2 presents a packing model of the testing granular medium; fine fragment is increased from a low 10% in Fig 2a to a high 50% in Fig 2d. The particle size disparity ratio (i.e. the mean sand diameter to silt diameter ratio) is about 13 and particles are illustrated, for presentation purposes, as perfect spheres. In Fig 2a, columnar chains of particles convey the skeletal forces that are stemmed from and along the direction of applied principal stress. At this moderate silt content (>2.5% energy in LBF, >20% in LBM, >75% in WCS), the fine fragment spreads throughout the trans-assemblage pore phase and only carry minimal skeletal forces. The survival chance of particles is studied in conjunction with shape proxy parameters in Section 4.3.

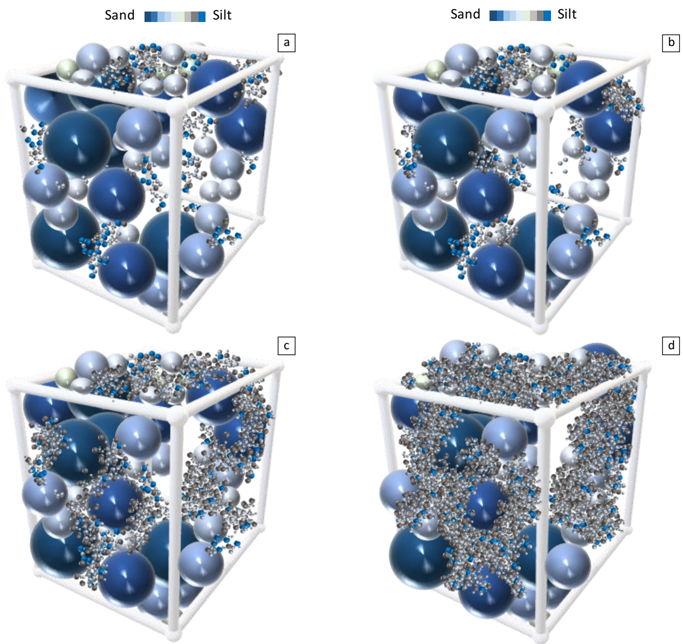

Figure 2. Conceptual model for sand-to-silt transition [a] 10% silt population, [d] 50% silt population

4.2 *Universal Modes*

Figure 1a-d shows favoured modes that are common in sands of all regions. Particles sizing 10-17μm, 45-47μm and 56-58μm are favoured across all groups of sands and hence can be cautiously regarded as universally favoured modes. Favoured modes are consistent with pronounced mode sizes broadly reported for loess and extends the origin of loess silt component from Periglacial to Peridesert and Perimountain quartz. Particles sizing 30-34μm and 106-193μm were found to be unfavoured in all groups and can be cautiously regarded as universally unfavoured modes.

4.3 *Particles' Shape and Chance of Survival*

Common to survived particles is an R=0.25±0.02 roundness (see 56μm mode for WCS under 75% effort, and 45μm mode for WCS under 15% effort, both modes common with pronounced 56μm and 45μm modes in CRS). Survived particles can develop fresh internal cleavage planes near surficial chevron-shaped cracks (Assadi-Langroudi et al. 2014) should these exist. Figure 3 compares the textural and morphological quality of two WCS sand grades. Figure 3a-b shows a crystalline intact particle under 75% level of impact energy. The survived particles contain neither V-groove features nor signatures of internal defects. Figure 3c-d present a 68μm WCS particle under 10% level of impact energy. The survived particle contains taxonomical anomalies near existing chevron depression. The particle diameter is a common mode (see Section 4.1) and hence subjected to further size reduction. Common to particles within the range of unfavoured modes is an S=0.68±0.03 sphericity.

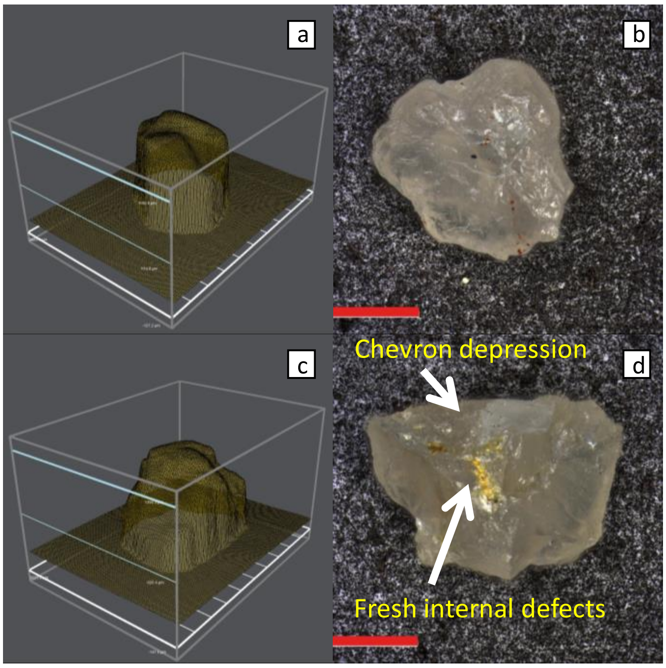

Figure 3. Morphology of WCS [a]-[b] Survived particle (56µm, 75% energy, universal favoured mode), [c]-[d] Survived particle (68µm, 10% energy, alternating mode, crushable upon fatigue)

5 CONCLUSIONS

In both defected Periglacial and mature Peridesert sands, fragmentation begins at sands' fine fraction. Larger particles function as clasts and break finer sand particles into the silt fragment. Where the silt output forms large volumes, coagulation may 'weld' powdered silts to form peds of 800-1000µm in size. The latter appears to be one universally favoured size for sand. Along the comminution, common modes receive and lose particle population as favoured and unfavoured modes alternate. There does not appear to be any universal common mode. As such, crushability of sand is not necessarily a factor of energy. Survived particles may still break on prolonged application of small and transient efforts and on formation of fresh internal imperfections that form near surficial chevron-shaped cracks should these exist. This is often regarded as fatigue fracturing. No universal common mode was found. Fatigue fracturing as an ageing phenomenon appears to be common to sands of any origin and is most marked in mature Peridesert sand. The size diminution generates universal favoured and unfavoured modes: Particles sizing 10-17µm, 45-47µm and 56-58µm are favoured across all sand groups and can be cautiously regarded as universally favoured modes. Common to survived particles is an R=0.25±0.02 roundness. Particles sizing 30-34µm and 106-193µm were found to be unfavoured in all sand groups and can be regarded as universally unfavoured modes. Common to particles within the range of unfavoured modes is an S=0.68±0.03 sphericity.

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