Imprints in silica grains induced during an open-channel flow experiment

Costa, Pedro J.M.; Park, Yong Sung; Kim, Young Do; Quintela, Maria; Mahaney, William C. ; Dourado, Francisco; Dawson, Sue

Published in:
Journal of Sedimentary Research

DOI:
10.2110/jsr.2017.39

Publication date:
2017

Document Version
Peer reviewed version

Citation for published version (APA):
Costa, P. J. M., Park, Y. S., Kim, Y. D., Quintela, M., Mahaney, W. C., Dourado, F., & Dawson, S. (2017). Imprints in silica grains induced during an open-channel flow experiment: Determination of microtextural signatures during aqueous transport. Journal of Sedimentary Research, 87(7), 677-687. https://doi.org/10.2110/jsr.2017.39

IMPRINTS IN SILICA GRAINS INDUCED DURING AN OPEN-CHANNEL FLOW EXPERIMENT:
DETERMINATION OF MICROTEXTURAL SIGNATURES DURING AQUEOUS TRANSPORT

Pedro J. M. Costa[1,2,*], Yong Sung Park[3], Young Do Kim[4], Maria Quintela[1], William C. Mahaney[5], Francisco Dourado[6] and Sue Dawson[2]

[1]IDL, Universidade de Lisboa, Edifício C6, Campo Grande, 1749-016 Lisboa, Portugal. [2]Department of Geography, School of Social Sciences, University of Dundee, Nethergate, Dundee DD1 4HN, Scotland. [3]School of Science and Engineering, University of Dundee, Nethergate, Dundee, DD1 4HN, Scotland. [4]Department of Environmental Engineering, Inje University, 197 Inje-ro, Gimhae-si, Gyeongnam, 621-749, South Korea. [5]Quaternary Surveys, 26 Thornhill Ave, Thornhill, Ontario L4J 1J4, Canada. [6]Universidade do Estado do Rio de Janeiro, Faculdade de Geologia, Departamento de Geologia Aplicada, Brasil.

*Corresponding author: **{** HYPERLINK "mailto:ppcosta@ciencias.ulisboa.pt" **}**

Other email contacts: YS Park – **{** HYPERLINK "mailto:y.s.park@dunde.ac.uk" **}** ; YD Kim – **{** HYPERLINK "mailto:y.s.park@dunde.ac.uk" **}**; M. Quintela – **{** HYPERLINK "mailto:mariacmquintela@gmail.com" **}**; WC Mahaney – **{** HYPERLINK "mailto:arkose41@gmail.com" **}**; F. Dourado - **{** HYPERLINK "mailto:fdourado@cepedes.uerj.br" **}**; S Dawson – **{** HYPERLINK "mailto:s.dawson@dundee.ac.uk" **}**

ABSTRACT

The aim of this work is to identify and characterize microtextural signatures in silica\glass grains (used as analogous to quartz) that are produced during aqueous transport at different flow velocities, with variable sediment concentrations, transport distances, and time intervals. To achieve this, an open-channel flow experiment was conducted with a mixture of sand and silica\glass microspheres in varying conditions – velocity (from 0.67 to 1.4 m/s), duration (1 or 10 minutes), distance (0 to 2.5 m) and sediment concentration (60% or 80%). Experimental conditions were used to replicate natural phenomena such as river superficial velocity or coastal swash processes.

Before to the experiment the microsphere surfaces were imaged and clear of any microtextural imprint. Increasing velocity, distance, and sediment concentration exhibited a strong correlation with higher numbers of surfaces abundantly covered with microtextures of mechanical origin (i.e., craters, abrasion marks, and v-shaped percussion marks). SEM microphotographs of silica were analyzed and classified to provide examples of the specific microtextures produced during the open-channel flow experiment.

The purpose of the experiment was to characterize surface microscopic signatures in quartz grains replicating hydrodynamic conditions of coastal and fluvial environments. The results demonstrated a strong correlation between higher velocities (and higher sediment concentrations) and a larger presence of microtextural mechanical imprints in the grains analyzed, thus demonstrating a clear relation between microtextural imprints and water flow modes. These results have important implications for future microtextural works analyzing grain imprints and their relation to sediment transport types. An example demonstrated here is that the higher presence of v-marks could be used as an indicator of supercritical flow conditions.

KEYWORDS

Microtextures; aqueous transport; open-channel flow; percussion cracks; sediment transport; quartz

INTRODUCTION

Prior microtextural research focused on defining affinities with specific geological processes. For example, Krinsley and Doornkamp (1971) and Mahaney (2002) postulate (but did not experimentally test) a correlation between v-shaped percussion (mechanical) cracks (Figure 1) and aqueous (fluvial) transport. Furthermore, they state that the frequency of percussion microtextures may be related to various fluid velocities (Mahaney et al. 2011. The aim of this work is to identify and characterize microtexture (mechanical) signatures in glass grains (> 70% SiO_2 - used as analogous to quartz) produced during aqueous transport at different velocities, with changing sediment concentrations, over variable distances and time intervals.

Numerous efforts (e.g., Krinsley and Margolis 1969; Pyokari 1997; Abu-Zeid *et al.* 2001; Mahaney 2002; Bull and Morgan 2006; Costa *et al.* 2009; Deane 2010; Costa et al. 2012; Costa et al. 2013; Vos et al. 2014, Bellanova et al. 2016) have been made to characterize surface microscopic signatures in quartz grains from a range of diverse sedimentary environments, but all are inferential and based on contingent geological variables. The results proposed have been not consensual in the interpretation of specific microfeatures and in the interpretation of some imprinting mechanisms or processes. However, v-shaped percussion cracks, first identified by Krinsley and Dornkamp (1973) and further studied in detail by Mahaney (2002) and Mahaney et al. (2010) in many fluvial settings, showed that such microfeatures were not only confined to aqueous transport but in extreme cases (tsunami events) quartz surfaces could be nearly totally resurfaced with the v-shaped pattern (Fig. 1). To date, the association of specific microtexture signatures with specific sedimentary environments is still debated, and many believe that some microtextures are produced in several different microenvironments; hence the **principle of equifinality.**

Although much has been achieved, it is important to standardize the definition of microtextural features and to show through experimentation that it is possible to match geological process with particular microtextures seen under electron microscopy. The work presented here aims to contribute to a clearer identification of microtextures associated with transport in aqueous environments, in particular under supercritical-flow conditions.

MICROTEXTURAL MECHANICAL IMPRINTS AND THEIR ASSOCIATION WITH MODES OF TRANSPORT

The application of grain microtexture analysis in sedimentology - using images obtained by Scanning Electron Microscope (SEM) - was initiated by Kuenen 1959, Biederman 1962 and Krinsley and Takahashi 1962. Microtextures are features of microrelief (observed using photomicrographs obtained with the SEM) on the surface microfabric of sediment particles, which are independent of the shape, size, and roundness of the particle. This analysis, also called exoscopy, is based on similar principles as morphoscopy; thus, assuming that some microtextures may be inherited from source material with others imposed by sedimentary processes on the surface of the grain during the course of its history and transference from one microenvironment to another. This research involves observations of microtexture images magnified with a Scanning Electron Microscope (SEM), up to $x10^4$, in contrast to the maximum magnification of $x10^2$ achieved with the binocular microscope.

Microtextural analysis has focused mainly on quartz, selected because of its ubiquity in terrigenous sediments, although some workers have focused research on heavy minerals (e.g., Mahaney 2002; Moral Cardona et al. 2005). Interpretations about processes responsible for microfeatures are occasionally disputed, mainly because of the lack of firm definitions for each microtexture and the degree of subjectivity introduced by different operators. However, several studies (e.g., Williams et al. 1998; Mahaney 2002; Peterknecht and Tietz 2011; Udayaganesan et al. 2011; Costa et al. 2012; Costa et al. 2013; Vos et al. 2014; Bellanova et al. 2016) demonstrate progress in the application of this methodology by applying semi-quantitative approaches and developing stronger links with geological processes to confirm microtexture analysis as a technique of considerable utility, particularly in provenance studies.

Work by Mahaney (2002), commonly used as a microtexture atlas, characterizes a group of forty-one different microtextural features suggesting their association with specific environments (e.g., percussion cracks to aqueous environments; bulbous edges and abrasion fatigue to aeolian environments). Madhavaraju et al. (2009) examined quartz grains under the scanning electron microscope and defined thirty-two distinct microtextures grouped into three modes of origin, i.e., mechanical (eighteen features), mechanical and/or chemical (five features), and chemical (seven features). However, even in the same sedimentary environment, changes were detected from one to the other group, as one might expect. In agreement with these findings, Manickam and Barbaroux (1987) observed that in the Loire River (France) chemical features are dominant during winter while mechanical features dominate during the summer.

Following the work of Krinsley and Wellendorf (1980), Willetts and Rice (1986) and Lindé and Mycielska-Dowgiallo (1980), Costa et al. (2013) conducted a wind-tunnel experiment, using glass spheres (> 70% SiO_2) as a proxy for quartz, with the objective of determining the extent of mechanical damage to silica transported in a mixture with quartz beach sand. The experiment proved that aeolian transport over short distances and during a relatively short period of time is enough to imprint significant abrasion on microspheres, leading to polished surfaces in some cases. The microtextures produced were fresh surfaces, abrasion fatigue, fractures (subparallel linear and conchoidal), and abrasion that covered imprinted areas of different sizes. A comparison of microtexture imprints on glass spheres relative to coastal dune sands was made to better understand energy thresholds required to achieve grain damage. However, one must consider the work of Lisá (2004), who observed that, in the case of typical aeolian sediments, about 10% of the fractions studied will not show any surface microtextures typical of aeolian transport, and hence, retain previously inflicted bedrock relief and grain damage, including pre-weathered microfeatures, prior to entrainment in a wind column. This conclusion has been applied to other sedimentary environments, particularly glacial systems, where 10% ± of thousands of grains studied sojourned without contact through hundreds of kms without detectable grain resurfacing (Mahaney 2002). Nearly complete grain resurfacing seems to occur only over long-distance transport (Mahaney 2002) and/or under extremely high-energy conditions with velocities > 10 m/s (i.e., tsunamis, Mahaney et al. 2010 and Costa et al. 2012).

Microtexture analysis of quartz grains subjected to aqueous transport has focused mainly on the identification of microfeatures observed without a full understanding or interpretation of the processes involved in the imprint of the microtextures. Moreover, site-specific constraints (e.g., sediment source) limit extrapolations elsewhere.

Costa et al. (2012) used approximately 4000 quartz grains from tsunami deposits and present-day analogs (nearshore, beach, dune, and alluvial samples) from a group of locations worldwide (Portugal, Indonesia, and Scotland) to characterize grains laid down by tsunami waves (transported in an aqueous environment) and to establish, whenever possible, the provenance of such grains. Their results point to the difficulties of assigning general microtextural features to specific sedimentary environments, even though, in some cases, the results proved conclusive and established likely sources for quartz grains transported and deposited by tsunami waves.

The microfeatures most commonly associated with aqueous transport are v-shaped percussion cracks. However, the origin of this feature has been a contentious matter (e.g., Campbell 1963; Mahaney 2002, Costa et al. 2012; Costa et al. 2013). Even if Campbell (1963) indicated that little evidence can be found to support the premise that percussion cracks on sand-size particles can be ascribed to an aqueous environment, others have inferred that such is possible. Moreover, Krinsley and Donahue (1968) suggested that river transport and turbidity currents do not impress specific surface microtextures on quartz sand grains even if after establishing that differences exist depending on the modes of transportation and deposition. Alternatively, Mahaney (2002), Madhavaraju et al. (2009), Deane (2010) and Costa et al. (2012) suggested that v-shaped patterns of mechanical origin (i.e., percussion cracks) originate mainly in subaqueous environments with high-energy conditions. Lindé and Mycielska-Dowgiałło (1980) tested grains (in sedimentary environments and experimentally in flumes) and noted that there are differences in the occurrence of the v-shaped microfeatures found in grains emplaced by natural as opposed to experimental processes, but their similarities nevertheless proved the grains were subjected to mechanical abrasion in aqueous environments.

In order to try to resolve some of the issues raised above, we set up a controlled experiment in an open-channel flow capable of replicating several conditions that occur in the coastal and fluvial natural environments, thus offering a possibility to gain a clearer understanding of the type and frequency of (mechanical) microtextures in quartz grains and determine their relationship with processes and mechanisms that occur during aqueous transport.

THE EXPERIMENT

The experiment was carried out in a recirculating water flume at the Environmental Water Resources Laboratory in the Department of Environmental Science and Engineering at Inje University, South Korea. The water flume is made of painted steel plates and measures 6 m long, 0.3 m wide and 0.3 m deep (Figs. 2A, 2B). The water flow is supplied by a high-elevation reservoir through five hoses (Fig. 2C). Each hose is fitted with an adjustable valve. The flow rate is controlled by adjusting the opening of the valves. The feed water enters into the pressurizing chamber before flowing into the working section of the flume, so that a very high flow velocity (up to 2 m/s with the nominal depth of 0.2 m) can be achieved. Between the pressurizing chamber and the working section of the flume, a hinged gate (see Figs. 2A, 2B) used to control the flow velocity.

The sediment used in the experiments is a mixture of 125-500 μm sand and glass microspheres (> 75% SiO_2) (see Table 1 for details). We used commercially available medium sand, composed predominantly of quartz grains, which was collected in Jeonnam, South Korea. The mixture consists of two thirds sand and one third microspheres by weight. The sediment was mixed with water for the desired sediment concentrations.

On the bottom of the flume and across its entire width two cylinders of right triangular cross section of 20 mm height were installed: one at 0.5 m from the upstream hinged gate and the other at 2.5 m. The water and sediment mixture was placed in this 20 mm high reservoir before each experiment (Fig. 3).

Sediment mixtures of sand and microspheres with two different concentrations in water, namely 60% and 80%, were used. Although lower concentrations were tried, the water and sediment mixture was immediately swept away as soon as the water flow was initiated, making it impossible to collect samples. For each of the sediment concentrations, three different flow conditions were used, and samples were collected after 1 minute and 10 minutes into the experiment at three different locations (at the upstream end, in the middle, and the downstream end of the reservoir). Water depth was measured at five equally spaced locations within the reservoir (0.5 m, 1.0 m, 1..5 m, 2.0 m and 2.5 m from the upstream gate) using tape rulers attached on one side of the flume. The flow rate was estimated by measuring the water depth and the flow velocity using a SonTek FlowTracker at the end of the flume. The hydrodynamic conditions are summarized in Table 2.

Experimental conditions were set to simulate, as accurately as possible (despite some scaling limitations e.g., length of channel), physical conditions (e.g., velocity, distance, etc.) that are observed in natural coastal and fluvial environments and their associated aqueous sediment transport in supercritical-flow conditions (Froude number > 1, Table 2).

METHODS

Microtexture analysis is generally reserved for sand-size particles obtained from detrital sediment. Once the sample is washed and dried, sieving is performed to separate the sample into several size fractions. The fraction typically used is the 1-3 phi (125-500 µm) (of sediment and microspheres size characteristics are summarized in Table 1). Within this fraction, sand grains are chosen randomly under the binocular lens.

The authors' own experience suggests 12 grains as a minimum of grains to be representative of a sample, although it is advisable to take this number to a value closer to 30 (statistical representativeness of results have been discussed in Costa et al., 2012; Vos et al., 2014 and Bellanova et al., 2016). Each separated grain is subsequently coated with Au or C, the samples mounted on the stub, and taken to the SEM, where images (photomicrographs; one grain per photo) are obtained and afterwards used to depict and characterize the micromorphology of the grains. Microphotographs were obtained using a JEOL JSM 5200 LV scanning electron microscope at the SEM laboratory (Faculdade de Ciências da Universidade de Lisboa).

Several microphotographs of microspheres were taken before the experiment to serve as control images in terms of microtextural signatures (Fig. 3).

The laboratory procedure, is followed by the visual identification of the microtextures imprinted in the surface of the grains. The first approach is to semiquantify the percentage of the grain that is imprinted (*vestigial, rare, present, dominant, and overwhelming dominant* – 0 - 10%, 10 - 25%, 25 - 50%, 50 - 75% and > 75% of the surface, respectively). This work is of particular relevance because the microspheres had no microtextural marks before the experiment (Figure 4).

The identification of specific microtextures is based upon reference works (e.g., Mahaney 2002). Each grain is characterized based on a set of microtexture attributes imprinted on its surface. Thereafter, the presence of each microtexture in each grain is classified according to the percentage of the surface of the grain it occupies: [0] - absent (i.e., 0% of the surface occupied by the microtexture) to [5] (> 75% of the grain's surface occupied by the microtexture). The grains analyzed in this work exhibited, as expected, mechanical marks. Therefore, we focused on the most common mechanical marks present (i.e., craters, abrasion microfeatures, and percussion cracks) that were classified in each grain. These features can be characterized as follows:

Craters - identifiable by the occurrence of a depression (open or closed) on the surface of the grain, caused primarily by mechanical impact or by rasping caused by grains in traction rubbing against fixed surfaces (i.e., bedrock) (Fig. 1B).

Abrasion - microtexture indicating surface erosion, producing streaks, alignments, and other lineations as a result of friction or scratching caused by collision or prolonged contact between grains (Fig. 1C).

Percussion cracks - usually correspond to v-shaped excavations (with variable dimensions, symmetric or asymmetric) on the grain surface (Fig. 1A).

Median values are calculated for each sample (group of unspecified n grains classified). Statistical analysis (e.g., cluster and principal-components analysis) are applied to the data obtained. The authors have successfully used the nonparametric Kruskal-Wallis test (Kruskal and Wallis 1952) to ensure the statistical significance of the results.

RESULTS

After the experiment, several groups of microphotographs were obtained from the experimental suites of grains corresponding to conjugated sets of specific conditions (time, sediment concentration, velocity).

Silica microspheres were classified in terms of the percentage of the grain surface occupied by the new microtextures imprinted during the experiment (vestigial, rare, present, dominant, and overwhelmingly dominant). Variation of these percentages with the varying experimental conditions are shown in Table 3.

Three main mechanical microtextures were detected in all samples: craters (Fig. 5), abrasion marks (Fig. 6) and percussion cracks (Fig. 7). The presence of three main types of mechanical cracks was classified having in consideration the area of the grain's surface each occupied after each run (Table 3, Fig. 8). Departing from the initial microspheres (with no mechanical imprints on its surface), it was possible to determine that approximately 30% to 50% of grains presented new mechanical microtexture imprints (Table 3).

It is important to note that for the analyzed grain assemblage, and from those grains exhibiting new microtextural imprints, the large majority (app. 70%) exhibited vestigial or rare marks (reduced areas of the grain presented mechanical microfeatures). In contrast, combined values of overwhelmingly dominant and dominant imprints were typically around 15% of the grains with new imprints (Table 3). Thus, from the initial set of grains per sample only a reduced number (around 5 - 10%) revealed relevant or nearly total resurfacing with new imprints resulting from the flume experiment.

Sediment Concentration

The results indicate that the percentage of imprinted grains is nearly identical (approximately 45%) in the varying sediment concentrations used (i.e., 60% and 80%) (Table 3). It is also apparent that the stronger presence of microtexture microfeatures was observed in the 80% -Sediment Concentration grains (mean value of 8.2% - Overwhelmingly dominant) when compared with the 60%- Sediment Concentration grains (mean value of 5.4% - Overwhelmingly dominant). With reference to the three main microtexture microfeatures (i.e., craters, abrasion microtextures, and percussion cracks), it was detected that the mean values for each one of these are very similar in both types of sediment concentration. However, when the maximum values are analyzed it is clear that craters and especially percussion cracks exhibit similar mean maximum values (4.125%) in the 80% Sediment Concentration samples (Table 3, Fig. 8). Likewise abrasion marks present higher mean maximum values in the 80% Sediment Concentration samples while craters present higher values in the lower-concentration samples (Table 3).

Time

In terms of time, the mean value of the percentage of imprinted grains is slightly higher in samples transported for 10 minutes than in samples after the 1 minute run (Table 3). All mean values for craters, abrasion microfeatures, and percussion cracks are similar in both the 1-minute-run group as well as the 10-minute-run group (Table 3). However, it is important to note that mean and maximum values for craters and maximum values for abrasion cracks increase with time while percussion marks slightly decrease with time (Table 3, Fig. 8).

Distance

As expected, the percentage of imprinted grains clearly increases with increasing distance (Table 3). The same pattern is observed in the sum of overwhelmingly dominant and dominant percentage values – presenting mean values of 13.5%, 14% and 19.8% for 0.5m, 1.5m and 2.5m, respectively. Interestingly, the sum of vestigial and rare microfeatures displays values of 70%, 71%, and 71% (for 0.5 m, 1.5 m and 2.5 m, respectively).

One microtexture change deserving attention is the mean value of abrasion microfeatures that clearly increase with distance 0.07%, 0.3% and 0.64% for 0.5 m, 1.5 m and 2.5 m, respectively (Table 3). A similar trend is observed for the maximum values for abrasion microfeatures and percussion cracks which also increase with distance (Table 3, Fig. 8).

Velocity

In the analysis of microtextural imprints and their association with varying velocities, one should take into consideration the varying number of samples between different velocities used (0.671 m/s, 0.772 m/s, 0.881 m/s, 1.004 m/s, 1.045 m/s, 1.112 m/s, 1.147 m/s and 1.377 m/s).

Increased velocity overall produced an increasing percentage of imprinted grains and, in particular, a higher number of grains presenting (overwhelmingly dominant and dominant microtextures} (Table 3, Fig. 8). It was observed that only the presence of percussion cracks increased with velocity (Table 3).

DISCUSSION

The main differences between common quartz grains and glass microspheres used is density- slightly lower than common quartz grains (Table 1). Nevertheless, despite variations in hardness and density, the use of this approach has been followed in the past with success to determine microtextural characteristics (e.g. Costa et al., 2013). Despite some minor scaling limitations (the length of the open-channel was limited to 6 m), it was possible to replicate velocities commonly observed in rivers or swash zones (supercritical flow). This type of flow condition is particularly common in tsunamis, storms, or major flood events; thus it is of major interest to detect what type of imprints are carved in grains transported during these natural hazards.

Our initial analysis focused on the identification of the most common microtexture imprints in the microspheres. It is clear that the most dominant are craters, abrasion microfeatures, and percussion cracks (Figures 5, 6, 7). All of these features result from short-lived mechanical impacts between grains. This contrasts with the absence of other microtextural features like dissolution or precipitation that are confirmed as the result of longer-term processes. However, the percentage of imprinted grains per sample only increased with time and it seemed to be relatively unaffected with higher sediment concentrations, distance, and velocity. We can consider a variety of reasons for these conclusions.

First, the hydrodynamic conditions used in this experiment were very specific (Table 2), in particular the (high) sediment concentrations and varying velocities used. This offers a better control of sediment and water flow (decreasing its velocity), but as a consequence we also increased the likelihood of inter-grain mechanical impacts, even if grains had less space to gain velocity before impact. With the sediment concentration used in this experiment, sediment would tend to move by grain collision - when volume concentration is greater than 9% (Bagnold 1962). Furthermore, Mulder and Alexander (2001) and Hsu (2004) suggested that sediment mixtures greater than 40% sediment-volume concentrations are no longer supported by fluid turbulence, because grain interactions play the dominant role. Thus, in our experiment results obtained should take into consideration the fact that sediment volume might be responsible for the additional presence of mechanical impressions. Nevertheless, the experiment described here provides clear insight into the generation of the mechanisms involved to produce aqueous signatures and identifies variations on the presence of some microtexture marks under supercritical flow.

Despite the fact that the percentage of imprinted grains might have been exacerbated by the high sediment concentration used, results obtained show that the difference in the presence of imprinted grains between 60% and 80% sediment concentrations is not relevant, probably because we used concentrations above 40% (where grains are moved essentially by inter-grain actions and not by fluid flow). Such variable concentrations probably occur in nature where sand source sediment is in variable supply. Thus, future work should test smaller sediment concentrations to determine if sediment concentrations below 9% or 40% show a smaller number of imprinted grains per sample.

Another relevant aspect from this experiment is that an attempt to explain how some grains have passed through the whole length of an open-channel flow without a single imprint. As has been detected in other field studies, simple random chance is responsible for the occurrence of inter-grain impacts most probably related to time of entrainment of grains, distance transported, and sediment concentration. This aspect raises questions regarding the minimum number of samples necessary to access microtexture results. Mahaney (2002) and Costa et al. (2012) provided empirical data from groups of samples from a variety of sedimentary environments, proposing > 20 as the minimum number of grains to obtain statistically significant results. Other authors subsequently (e.g., Vos et al. 2014) also used a similar number of grains for their microtexture provenance studies. Moreover, Bellanova et al. (2016) used a larger number of grains per sample (> 100 grains) but with no features observed that differentiate different sedimentary environments, which was probably due to local sedimentary and geomorphological conditions, or because observations were made on only one size fraction which might have masked some of the distinctive characters of the grains. Costa et al. (2012) observed that quartz grains larger than 1 phi tend to present more dissolution features than those smaller than 3 phi (as a consequence of the smaller mobility of the latter). In this work we observed on average 21 grains per sample, and although obviously interpretations would benefit from a larger number of samples, results provided sufficient discrimination to allow differentiation of each specific microtexture, especially when a statistical (principal components) analysis was used to interpret results (Figure 9). Clearly the larger the dataset the more reliable it will be, but it is important that for comparison the same sediment fraction is analyzed.

A test of sediment concentration and velocity (Fig. 9) clearly shows that Axis 2 demonstrates the association between variables with a larger presence of overwhelming dominant types of grains (those with larger areas imprinted). These results make evident an association between increasing velocities and sediment concentrations producing larger presence of craters, abrasion, and percussion marks. This result is of crucial importance for the sedimentological study of past and present extreme wave events (tsunami and storms; Costa et al. 2012 and Bellanova et al. 2016) because it suggests clearly that the physical conditions (flow velocity, sediment concentration, etc.) associated with tsunamis and storms are favorable to the imprinting of sediment grains with mechanical marks, thus an increase in such a signature is likely in tsunami and storm deposits.

The origin of microtexture mechanical marks has been debated over the years, and very few examples of experimental tests have been conducted to address this issue. One exception is the work of Lindé and Mycielska-Dowgiałło (1980), who noted that despite some minor differences in the occurrence of (v-shaped) percussion cracks, found embedded in natural and experimental sand grains, their origin is associated with aqueous transport. In this experiment we were able to correlate higher values of percussion cracks associated both with higher sediment concentration and velocity, thus confirming a mechanical origin for percussion cracks and associating these with an aqueous medium under high-energy conditions as suggested by Mahaney (2002), Madhavaraju et al. (2009), Deane (2010), and Costa et al. (2012) based in field data. Also, Mahaney et al. (2016) showed a relation between increasing stream discharge and the frequency of v-shaped percussion cracks in a grain mix of carbonates and silicates from the end of glaciation in southern Ontario to generation of a floodplain in the middle Holocene. Our results provide experimental data that can be useful to validate interpretations of the geological record of tsunami, storm, and flood events.

CONCLUSIONS

To test microtexture carving mechanisms in quartz grains, an open-channel flow experiment was undertaken using a mixture of dune sand and silica microspheres under a range of conditions – velocity (from 0.67 to 1.4 m/s), time (1 or 10 minutes), distance (0 to 2.5m), and sediment concentration (60% or 80%).

Despite different experimental conditions a considerable percentage of Silica grains were imprinted (on average 50% of the grains analyzed presented some marks) in all varying conditions – the high values of imprinted microspheres might be the result of slight differences in hardness and density when compared with quartz. Nevertheless, results demonstrated that the most dominant microtexture features present were craters, abrasion marks, and percussion cracks. All of these features resulted from short-lived mechanical impacts between grains. In addition, results also showed the absence of other microtextural features like dissolution microfeatures or precipitation coatings because they are the result of longer-term processes. Also, conchoidal and subparallel fractures were not observed.

The experiment conducted established an association between increasing velocity and sediment concentration producing a greater presence of mechanical microtextural features such as craters, abrasion and percussion fractures. This result is crucial for the development and use of grain microtextural analysis in sedimentological studies of (paleo)flood events (river floods, storms, and tsunamis).

These results also enhance the use of grain microtexture analysis in sedimentological research, namely in grain transport under different discharge conditions with the provision that varying distances of transport are difficult, if not impossible, to replicate in the laboratory. The work presented here contributes to a better understanding of the mechanisms and processes involved in the mechanical imprint of microtexture features in quartz grains during aqueous transport.

ACKNOWLEDGMENTS

The authors acknowledge the collaboration of BSc students during the experiment conducted at the Department of Environmental Engineering, Inje University, South Korea. Pedro J.M. Costa benefited from a Post-Doctoral grant (SFRH / BPD / 84165 / 2012) from the Portuguese Science Foundation. William C. Mahaney benefited from financial support from Quaternary Surveys. The cooperation with Telmo Nunes (CBA, University of Lisbon) was essential to obtain the SEM microphotographs.

REFERENCES

Abu-Zeid, M.M., Baghdady, A.R. and El-Etr, H. A., 2001, Textural attributes, mineralogy and provenance of sand dune fields in the greater Al Ain area, United Arab Emirates: Journal of Arid Environments, v. 48. p. 475-499.

Bagnold, R.A., 1962, Auto-suspension of transported sediments: Proc. Royal Society, Series A, v. 236, p. 315-319.

Bellanova, P., Bahlburg, H., Nentwig, V. and Spiske, M., 2016, Microtextural analysis of quartz grains of tsunami and non-tsunami deposits – A case study from Tirúa (Chile): Sedimentary Geology, v. 343, p. 72–84.

Biederman, E.W., 1962, Distinction of shoreline environments in New Jersey: Journal of Sedimentary Research, v. 32[2], p. 181-200.

Bull, P.A. and Morgan, R.M., 2006, Sediment Fingerprints: A forensic technique using quartz sand grains: Science & Justice, v. 46, p. 107-124.

Campbell, D.H., 1963, Percussion marks on quartz grains: Journal of Sedimentary Petrology, v. 33[4], p. 855-859.

Costa, P.J.M., Andrade, C., Freitas, M.C., Oliveira, M.A. and Jouanneau, J.-M., 2009, Preliminary results of exoscopic analysis of quartz grains deposited by a palaeotsunami in Salgados lowland (Algarve, Portugal): Journal of Coastal Research, v. SI56, p. 39-43.

Costa, P.J.M., Andrade, C., Dawson, A.G., Mahaney, W.C., Paris, R., Freitas, M.C. and Taborda, R., 2012, Microtextural characteristics of quartz grains transported and deposited by tsunamis and storms: Sedimentary Geology, v. 275–276, p. 55-69.

Costa, P.J.M., Andrade, C., Mahaney, W.C., Marques da Silva, F., Freire, P., Freitas, M.C., Janardo, C., Oliviera, M.A., Silva, T. and Lopes, V., 2013, Aeolian microtextures in silica spheres induced in a wind tunnel experiment: comparison with aeolian quartz: Geomorphology, v. 180–181, p. 120–129.

Deane, S.M., 2010, Quartz grain microtextures and sediment provenance: Using scanning electron microscopy to characterize tropical highland sediments from Costa Rica and the Dominican Republic: Master's Thesis, University of Tennessee, 122 p.

Hsu, K.J., 2004, Physics of Sedimentology: Berlin, Germany, Springer, 2nd Edition, p. 240.

Krinsley, D.H. and Donahue, J., 1968, Environmental interpretation of sand grain surface textures by electron microscopy: Geological Society of America Bulletin, v. 79[6], p. 743-748.

Krinsley, D.H. and Doornkamp, J.C., 1973, Atlas of quartz sand surface textures: Cambridge, UK, Cambridge University Press, 91 p.

Krinsley, D. and Margolis, S., 1969, A study of quartz sand grain surface textures with the scanning electron microscope: Trans. N.Y. Acad. of Sci., v. 31, p. 457.

Krinsley, D. and Takahashi, T., 1962, The surface textures of sand grains: an application of electron microscopy: Science, v. 135, p. 923-925.

Krinsley, D. and Wellendorf, W., 1980, Wind velocities determined from the surface texture of sand grains: Nature, v. 283, p. 372-373.

Kruskal, W.H. and Wallis, W.A., 1952, Use of ranks in one-criterion variance analysis: American Statistical Association Journal, v. 47[260], p.: 583-621.

Kuenen, P.H., 1959, Transport and sources of marine sediments: Geol. en Mijub.,v. 21, p. 191-196.

Lindé, K. and Mycielska-Dowgiallo, E., 1980, Some experimentally produced microtextures on grain surfaces of quartz sand: Geografiska Annaler, Series A, Physical Geography, v. 62[3/4], p. 171-184.

Lisá, L., 2004, Exoscopy of Moravian eolian sediments. Bulletin of Geosciences, v. 79[3), p. 177-182.

Madhavaraju, J., García y Barragán, J.C., Hussain, S.M. and Mohan, S.P., 2009, Microtextures on quartz grains in the beach sediments of Puerto Peñasco and Bahia Kino, Gulf of California, Sonora, Mexico: Revista Mexicana de Ciencias Geológicas, v. 26[2], p. 367-379.

Mahaney, W.C., 2002, Atlas of sand grain surface textures and applications: Oxford, UK, Oxford University Press, 237 p.

Mahaney, W.C. and Dohm, J.M., 2011, The 2011 Japanese 9.0 magnitude earthquake: Test of a kinetic energy wave model using coastal configuration and offshore gradient of Earth and beyond: Sedimentary Geology, v. 239[1-2], p. 80-86.

Mahaney, W.C., Dohm, J., Costa, P. and Krinsley, D., 2010, Tsunamis on Mars: Earth analogues of projected Martian sediment: Journal of Planetary and Space Science, v. 280, p. 236-245.

Mahaney, W.C., Hancock, Ronald G.V., Somelar, Peeter and Milan, Alison, 2016, Iron and Al soil/paleosol extractions as age/environment indicators: some examples from a catchment in Southern Ontario, Canada: Geomorphology, v. 270, p. 159-171.

Manickam, S. and Barbaroux, L., 1987, Variations in the surface texture of suspended quartz grains in the Loire river: an SEM study: Sedimentology, v. 34, p. 495-510.

Moral Cardona, J.P., Gutiérrez Mas, J.M., Sánchez Bellón, A., Domínguez-Bella, S. and Martínez López, J., 2005, Surface textures of heavy-mineral grains: a new contribution to provenance studies: Sedimentary Geology, v. 174, p. 223-235.

Mulder, T. and Alexander, J., 2001, The physical character of subaqueous sedimentary density flows and their deposits: Sedimentology, v. 48, p. 269-299.

Peterknecht, K. M. and Tietz, G. F., 2011, Chattermark trails: surface features on detrital quartz grains indicative of a tropical climate: Journal of Sedimentary Research, v. 81, p. 153-158.

Pyökäri, M., 1997, The provenance of beach sediments on Rhodes, southeastern Greece, indicated by sediment texture, composition and roundness: Geomorphology, v. 18, p. 315-332.

Udayaganesan, P., Angusamy, N., Gujar, A. R. and Rajamanickam, G.V., 2011, Surface Microtextures of Quartz Grains from the Central Coast of Tamil Nadu: Geological Society of India Journal, v. 77, p. 26-34.

Vos, K., Vandenberghe, N. and Elsen, J., 2014, Surface textural analysis of quartz grains by scanning electron microscopy (SEM): From sample preparation to environmental interpretation: Earth-Science Reviews, v. 128, p. 93–104.

Willetts, B.B. and Rice, M.A., 1986, Collisions in aeolian saltation: Acta Mechanica, v. 63, p. 255--265.

Williams, A.T., Wiltshire, R. J. and Thomas, M. C., 1998, Sand grain analysis-image processing, textural algorithms and neural nets: Computers & Geosciences, v. 24,p. 111-118.

LIST OF TABLES

LIST OF FIGURES

Figure 1 – A) Detail of percussion cracks covering a quartz grain collected on a tsunamigenic deposit. B) Detail of craters observed in a grain collected in a dune environment. C) Detail of abrasion mark collected in a quartz grain collected in a beach environment.

Figure 2 – The high-speed water flume. A - Schematic diagram; B - the flume viewed from the downstream end; C - water-supply hoses connected to the pressurizing chamber of the flume.

Figure 3 – Experimental conditions with open channel structure and the water and sediment mixture (with 60% or 80% Sediment Concentrations). A) Photo illustrating the whole open channel in pre-experiment conditions with 60% Sediment Concentration. B) Photo displaying pre-experiment conditions observed at 1.5 m from the initial discharge point in the open channel (sediment mixture is at 60% Sediment Concentration). C) Photo illustrating experimental results at 1.5 m from the initial discharge point of the open-channel (sediment mixture is at 60% Sediment Concentration). D) Photo illustrating the whole open-channel in pre-experiment conditions with 80 Sediment Concentration. E) Photo displaying pre-experiment conditions observed between 1 m and 1.5 m from the initial discharge point in the open-channel (sediment mixture is at 60% Sediment Concentration). F) Photo illustrating experimental results at 1.5 m from the initial discharge point of the open-channel (sediment mixture is at 80%Sediment Concentration).

Figure 4 – A and B) examples of pre-experiment microspheres – please note the total absence of imprints on the surfaces of the grains'.

Figure 5 – Various microspheres grains with craters imprinted in their surfaces. A) Please note the large crater in the top of the grain. B) Please note the >50 µm crater on the top left region of the grain. C) Please note the >50 µm crater on the top left region of the grain and other minor craters on the right hemisphere of the grain. D) Please note top right region of the grain and its large crater. E) Single crater on the equatorial region of the grain. F) Please note the twin craters in the central region of the grain.

Figure 6 – Abrasion marks imprinted in the microspheres surfaces. A) Thin abrasion mark across the northern hemisphere of the grain. B) Circular abrasion mark on the central region of the grain. C) Deep abrasion marks on the lower left region of the grain. D) Small abrasion mark on the central region of the grain.

Figure 7 – Microspheres presenting abundant percussion cracks. (v-shaped marks). A) Percussion cracks visible in all regions of the grain, in particular in its southern hemisphere. B) Grain with several percussion cracks, in particular in its northern hemisphere. C, D) grain totally resurfaced with percussion cracks. E) Deep percussion cracks on the lower left region of the grain. F) Overprinted percussion cracks on the left equatorial region.

Figure 8 – Selected results displaying microtextural variation with different experimental settings. A) Exhibits the smaller maximum value of craters (Y-axis) with increasing sediment concentration value (X-axis). B) Displays the higher maximum value of craters (Y-axis) with increasing time (X-axis). C) Exhibits a decreasing pattern between the presence of craters (Y-axis) an increasing distance (X-axis). D) Exhibits a broad range of maximum values for percussion marks/cracks (Y-axis) in the 60% Sediment Concentration experiments and a smaller and higher range of values for the 80% sediment concentration tests (60% and 80% Sediment Concentrations are represented on the Y-axis). E) Displays an increase in the maximum values of abrasion marks (Y-axis) with increasing distance (X-axis). F) Displays a faint trend of increase of very dominant/overwhelming dominant grains (Y-axis) with increases in velocity (X-axis).

Figure 9 – Principal-components analysis on the whole grain assemblage analyzed, clearly showing that Axis 2 represents the association between variables with a larger presence of overwhelming dominant types of grains (those with larger areas imprinted) Discrimination is also visible analyzing Axis 2 presenting a good correlation between % Dominant and % Overwhelming dominant with velocity and partly with sediment concentration. Samples are represented by numbers as in Table 3.