



# Quantification of SEM quartz grain identifying the depositional environment

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## Abstract

Surface textural analysis of quartz by scanning electron microscopy (SEM) has been shown to be useful for identifying and discriminating depositional environments. Researchers used to compare the microtextures of bar graphs to determine the environment. However, the large number of variables in those plots makes it difficult to access data sets. In this work, we collected 14 riverbed sediment samples in the Yellow River and Qin River, China, and exploited semiquantitative classification of ternary diagrams and quantitative principal component analysis with Euclidean distance to address the task of differentiating among marine, eolian, fluvial, glacial, debris flow environments, and even subenvironments. The percent frequency of occurrence of microtextures on considerable quartz grains from a wide variety of environment is applied with this study and the reference works worldwide to invoke statistical comparison of different sample suites. These methods provided a quantitative means of measuring the differences among different environments and a quantification tool in assessing microtextures as a recorder of sedimentary environments. The results demonstrated that different sediments took up different spaces in the ternary plot. Eleven of 14 samples are correct when assigned to their corresponding environments using principal component analysis, which has distinct advantages over existing approaches for distinguishing depositional environment.

**Keywords** Microtexture · Quartz grain · SEM · Quantification · Principal component analysis

## Introduction

Microtextures of sand grains identified by scanning electron microscopic (SEM) are considered as indicative of provenance, depositional environments, and geological process (Gillott 1973; Krinsley and Donahue 1968; Mahaney 2002; Mahaney et al. 2001). Quartz, ubiquitous in nearly all environment (Vos et al. 2014), has a large hardness and high chemical stability, retaining almost microtexture features formed by transport and deposition process of various geological environments. Although researchers have investigated the features of microtextures of quartz grains under different

environments, how to use these characteristics to distinguish paleoenvironment effectively still remains as a problem.

Microtextures can be categorized as mechanical, chemical, and mechanical-chemical (Gillott 1973; Mahaney 2002). Accordingly, researchers have identified the major microtextures of quartz grains in fluvial, glacial, eolian, and coastal environments (Gillott 1973; Keiser et al. 2015; Krinsley and Trusty 1985; Mahaney 2002). Sand grains from fluvial show dissolution etching, craters, and abundant abrasion features with V-shaped percussion cracks dominating. Glacial grains are characterized by subparallel linear, steps, curved or straight grooves, and deep troughs whereas low relief and rounded edges are considered to be aeolian environment. The sand grains of high-energy beach are characterized by predominance of straight scratches, V-shaped percussion, smooth surfaces, and subangular outlines followed by medium relief, fracture planes, adhering particles, and minor etching (Armstrong-Altrin and Natalhy-Pineda 2014; Hossain et al. 2014; Immonen 2013; Keiser et al. 2015; Kirshner and Anderson 2013; Krishnan et al. 2015; Mahaney and Kalm 2000; Sweet and Soreghan 2010; Damiani et al. 2006; Hoesen and Orndorff 2004; Mahaney et al. 1996).

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Researchers used to compare the microtextures of bar graphs to determine the environment. The bar graphs have different shapes, suggesting that there are distinct signatures for each environment. However, the large number of variables in those plots makes it difficult to access data sets, unless there are strong contrasts in frequency data. Vast data from quartz grain surface microtextural studies should likewise be treated only through suitable statistical methods. Euclidean distance or similarity coefficient (Mahaney et al. 2001) was proposed to demonstrate the distance of different samples for classifying environment. However, preprocessing before calculating the distance, called principal component analysis (PCA), is required to compare with Mahaney's method provided that PCA analysis can project high-dimensional samples into low-dimensional space. The samples in the low-dimensional space therefore can to maximize the degree of dispersion, which makes it easier to classify the samples. Ternary diagram, famous for its intuition, has been presented by Sweet and Soreghan (2010) and Keiser et al. (2015). The apexes of ternary plot are high-stress fractures, percussion fractures, and polygenetic fractures respectively. Their plot has addressed the glacial and fluvial microtextures, but it is not comprehensive and systematic because eolian grain features have not been considered.

Fluvial systems vary from low, sluggish streams with a lower flow regime to fast-moving upper flow regime with high discharge, capable of moving boulder-size clast (Mahaney 2002). Streams may have different dominant microtextures of quartz grains which depend on the lithology of the source rocks, transporting distance, water composition, velocity of flow, and volume of water. Stream discharge is recognized as an important factor influencing the degree of abrasion and the frequency of V-shaped percussion cracks. Specifically, with high-speed direct collisions, kinetic energy released through grains resulting V-shaped percussion crack while in low-velocity collisions, energy is released into water instead of grains (Mahaney 2002). Despite its acknowledged importance, features of sand grains between lower flow regime and upper flow regime have not been well identified especially the lower flow regime.

The primary focus of this paper is to identify sediment environment based on the microtexture of quartz grain by quantitative methods and determine whether SEM imagery of quartz grains can discriminate between upper flow regime and lower flow regime. First, we sampled sands from the Yellow River and its tributary-Qin River to observe the surface of quartz by implementing SEM. Second, we compared our data with worldwide published data of quartz microtexture under different sediment environments and subenvironments. Specifically, we use agglomerative hierarchical clustering (AHC) analysis to classify microtextures into 3 groups according to distance or similarity, and plot a ternary diagram illustrating the distribution of different environments. In addition,

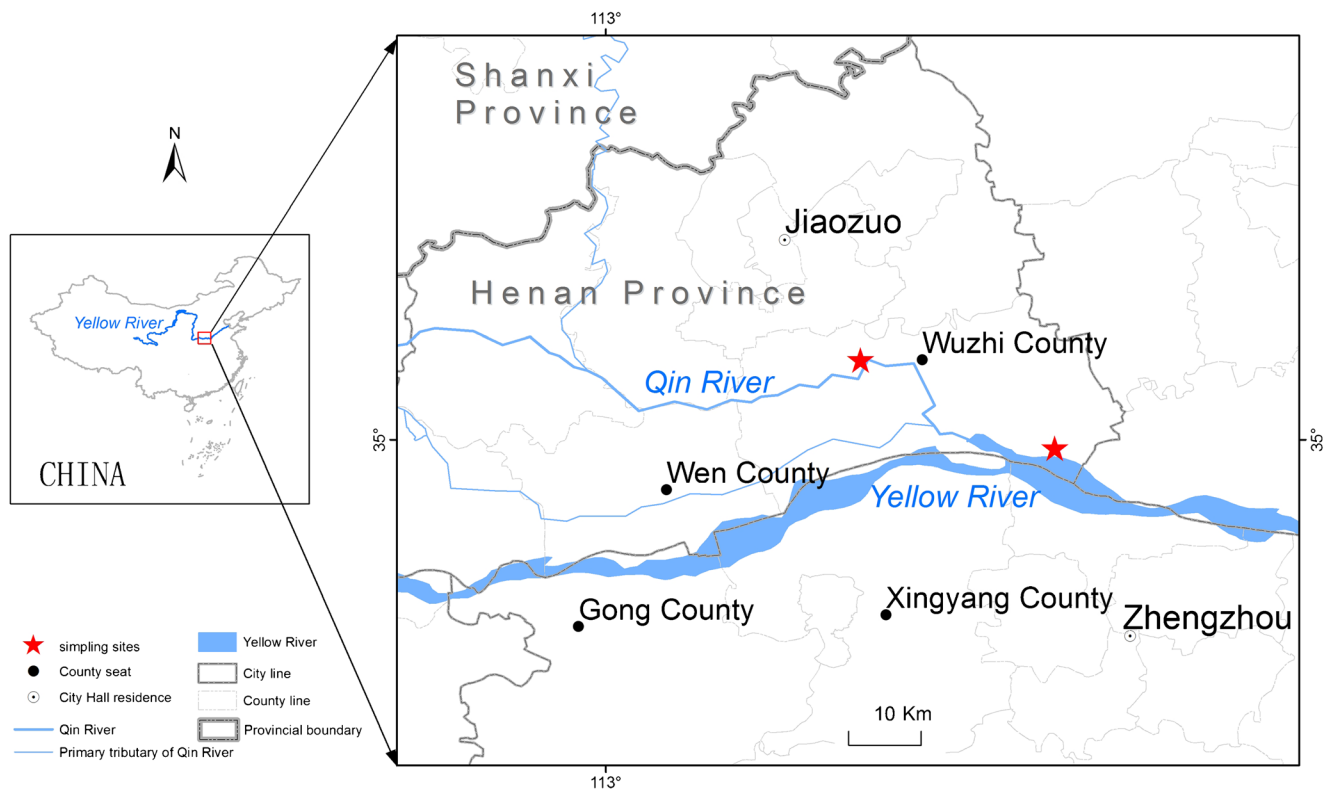
PCA analysis with Euclidean distance is used to compute similarities between test samples and environment categories according to standard samples, allowing us to attach the most relevant category to each test samples. The purpose of PCA analysis is to order the depositional environments based on summary microtexture observations to determine whether ordering reflects similarities or relationships among fluvial, marine, glacial, aeolian, and debris flow.

## Geological setting

The Yellow River, with a total length of 5464 km and a relief of 4830 km, has been divided into upper, middle, and lower reaches. The study area is located in dividing line between the middle reach and the lower reach of Yellow River, Jiaozuo, Henan, which is characterized by a relatively stable, low gradient, increasing erosion force. The middle reach of the Yellow River flows from Hekouzhen to Taohuayu, with a wide and frequently migrating channel. Due to rapid erosion, these reaches are characterized by hyperconcentrated flow, with maximum suspended sediment concentration up to  $1700 \text{ kg/m}^3$  (Xu 1998). The climate of this reach is semi-arid to arid, with unevenly distributed annual precipitation (Pan et al. 2016). Sandy storms occur in the spring, and the maximum wind speed reaches 25–30m/s (Yang and Wan-Quan 2004). Typical East Asian monsoon in the Yellow River causes southerly winds during summer and northerly winds during winter. Geologically, Yellow River drains diverse lithological units, including North China Block, South China Block, Qinling orogenic belt, Songpan-Ganzi orogenic belt, Quaternary detrital covers, and Loess Plateau (Pan et al. 2016; Yue and Liao 2016). The average flow velocity of Yellow River is  $2571 \text{ m}^3/\text{s}$  while Qin River is  $49.5 \text{ m}^3/\text{s}$ . Qin River drains a distance of 480 km and has a catchment of  $1350 \text{ km}^2$  extending from Qinyuan country, Shanxi province, to Wuzhi, Henan province, joining the Yellow River (Fig. 1).

## Methods

We collected 14 riverbed sediment samples in the Yellow River and Qin River. All of the sediments were collected from modern sedimentation and unaltered sand bars of the main channel. Prior to observe microtextures of quartz grains, organic matter and carbonates were removed from samples. The quartz grain separation methodologies were the same as those carried out in Vos et al. (2014). Firstly, sediments of 20 g of each sample were treated oven dry. Successively, samples were boiled for 10 min in a 15% HCL for removal of carbonates and iron oxides and washed with deionized water until the water was clear. Samples



**Fig. 1** Map of Yellow River and Qin River

were boiled for 10 min in a 50 g/L tetrasodium pyrophosphate solution for removal of clay, organic matter, and adhering particles and washed with deionized water until the water was clear. The samples are dried at 60°C and sieved using 600-, 300-, and 125- $\mu\text{m}$  sieves.

About twenty clean quartz grains (between 300- and 125- $\mu\text{m}$  size) from each sample were randomly selected for purity inspection and further observation with a stereo microscope. Samples were mounted on aluminum SEM stubs and sputter coated with gold-palladium to prevent charging. Surface microtextures were analyzed using SEM at the College of Resources and Environment, Henan Polytechnic University. The grains were analyzed by the Inca energy dispersive spectrometer (EDS) to confirm to be silica and their composite was captured with the high-resolution slow-scan digital image recording system SemAfore.

The surface microtextures of samples were recorded and sorted by mechanical, chemical, and mechanical-chemical textures. A total of 22 individual grain features and textures were traced from 220 analyzed quartz grains, and frequencies of these features were calculated as a percentage for each sample. In addition, the frequencies of microtextures of 34 samples under different sediment environment were collected from published papers all over the world for further quantitative study. In addition,

we unified the microtextures of quartz grain as the microtexture varieties in different papers.

The data were processed through agglomerative hierarchical clustering (AHC) by using the Pearson correlation coefficient similarity with single linkage. The statistical significance of microtexture distribution was calculated by sorting observations above the standard deviations that determine the average differing values of each observation. Variables were clustered by AHC, where variables with the shortest distance were discerned as having a strong indication of specific origin and samples with the shortest distance were considered as in the same environment.

Principal component analysis (PCA) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. In this study, to empirically evaluate our method, we use 60% of samples from each class clustered into five clusters represented with a mean feature vector respectively and evaluate on the rest, then compress high-dimensional vectors into lower dimensional vectors that we denote as mean feature vectors and feature vectors by applying PCA for both clusters and evaluated samples. Finally, we assigned each evaluated samples to the one of the clusters according to the minimum Euclidean distance between its feature vector and mean feature vector of the clusters.

## Results

In this study, we tested 122 quartz grain from the Yellow River-upper flow regime (Figs. 2 and 3) and 100 quartz grains from Qin river-lower flow regime (Fig. 4), and collected the data of 36 region samples quartz surface under different environments worldwide.

PCA analysis transforms the original data into a set of linearly independent representations by linear transformation, which can be used to extract the main feature components of the data, commonly used in dimensionality of high-dimensional data. Here, we considered the 22 microtextures as 22 dimensional. First, we divided randomly the data into two groups, 22 samples for the standard group and 14 samples for the test samples. Second, PCA was used to reduce dimensional of standard samples and test samples. Euclidean distance between a single sample to be tested and all standard samples were calculated and test samples were assigned to the shortest distance. Distance values (Table 1) confirm the hypothesis that different environments can be identified. They provide additional information, allowing the five environments to be ordered in a way that makes intuitive sense. Eleven samples were correct for the total 14 evaluate numbers. The correct percentage is 78.57%, which is proved to be a

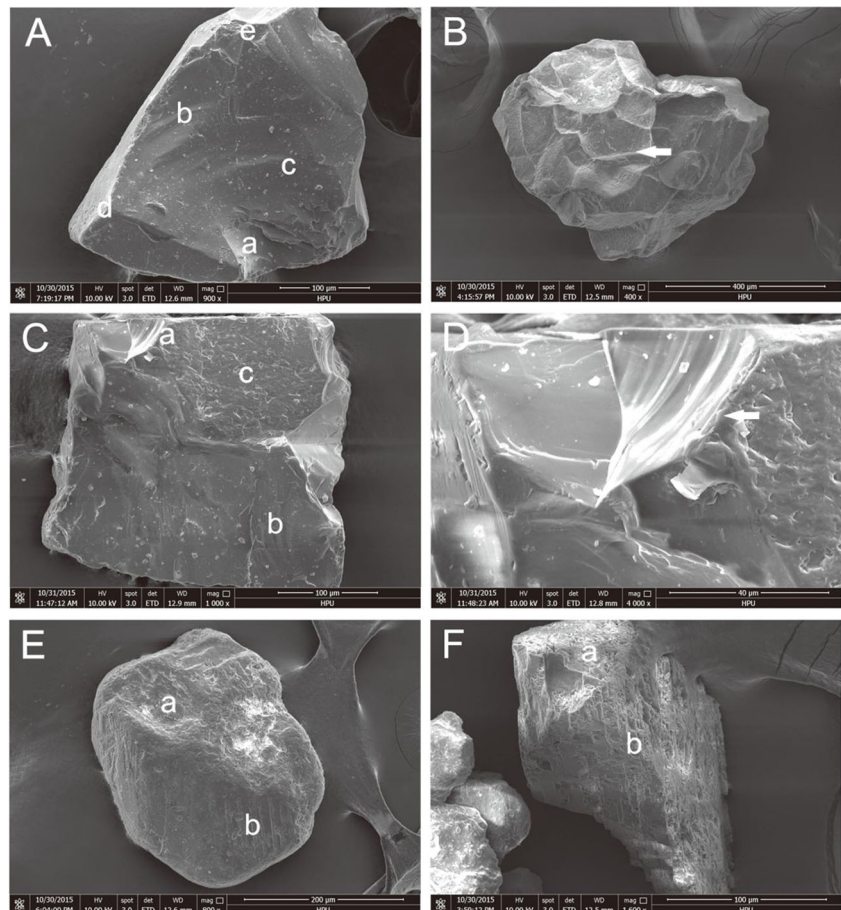
useful method. The advantage of this method is that we reduce the correlation and consider all the microtextures. As we are not completely confident that the standard samples represent the environment, we propose that the clustering center of the sample can represent the environment.

## Discussion

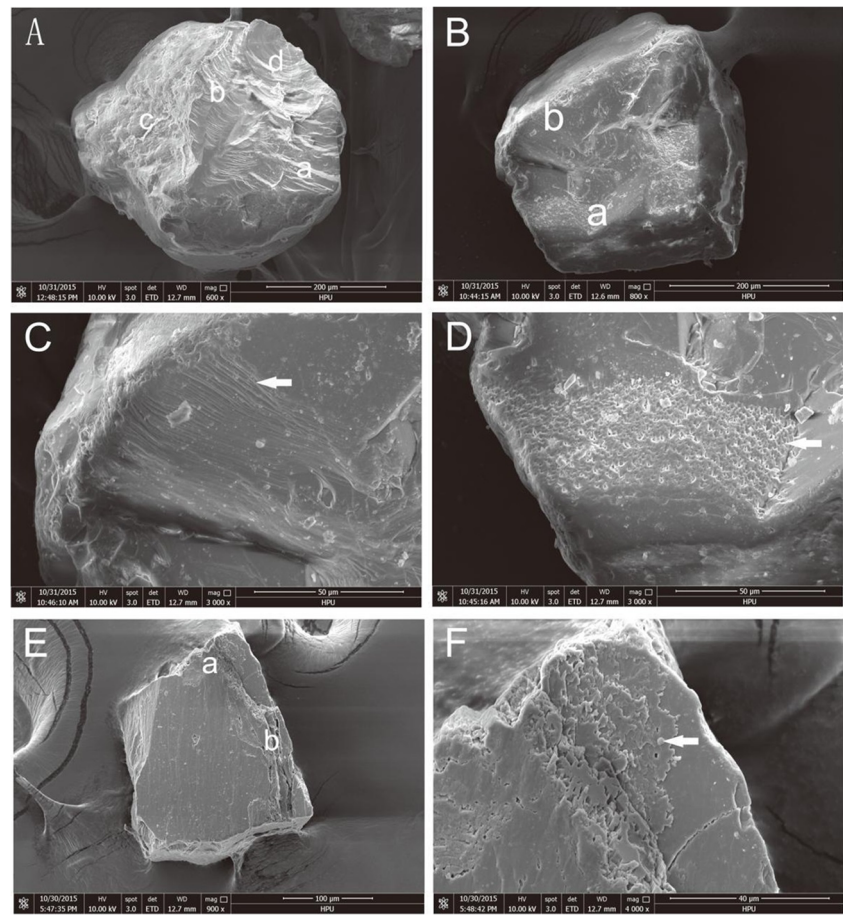
### Microtexture features

Totally, 22 microtextures of quartz were identified on the sand grains surface of Yellow River and Qin River (Fig. 5). The distribution of microtextures on sand grain from Yellow River and Qin River varied widely. Both Yellow River and Qin River were characterized by abundantly subangular grain, subparallel linear fractures (Fig. 3(E,b)), V-shaped percussion (Fig. 4(E)), and medium relief (Fig. 3(A,a)). Linear steps (Fig. 4(D,a)), V-shaped craters (Fig. 3), dissolution etching (Fig. 3(A,c)), and precipitation occurred commonly. Deep trough, curved grooves, upturned plates, and abrasion fatigue occurred sparsely. Furthermore, a subangular to subrounded outline and a medium relief were the most common shaped-related features in the Yellow River. Nevertheless, samples

**Fig. 2** SEM micrograph observed on sand grain from Yellow River. **A** Angular grains with conchoidal fractures (a), arc-shaped steps (b), adhering particles (c), V-shaped percussion (d), and fracture face (e). **B** Subangular grain with abundant V-shaped craters (arrow). **C** Subangular grain with conchoidal fractures (a); V-shaped percussion, arc-shaped steps, and abrasion features. **D** Magnification of conchoidal fractures. **E** Rounded grain with dissolution (a), scratches (b), linear steps, and V-shaped percussion. **F** Subangular grain with dissolution (a) and linear fractures (b)



**Fig. 3** SEM micrograph observed on sand grain from Yellow River. **A** Subrounded grains with medium relief, subparallel linear fractures, and linear steps (a); arc-shaped steps (b); dissolution etching (c); V-shaped cracks and conchoidal fractures (d); fractures faces and abraded fractures. **B** Subrounded grain with V-shaped percussion (a), linear steps (b), dissolution, and adhering particles. **C** Magnification of linear steps. **D** Magnification of V-shaped percussion. **E** Angular grain and precipitation (a); subparallel linear fractures (b). **F** Magnification of precipitation (arrow)



from the Qin River had a distinct abundance of angular grains and high relief. Yellow River was characterized by V-shaped percussion (Fig. 4(E)), dissolution etching (Fig. 3(c)), V-shaped craters (Fig. 3(d)), precipitation, and abraded fractures, whereas sharp angular features and curved grooves were properties of Qin River. It may be accounted for that sand grains in upper flow System-Yellow River have largely been transformed by water, such as collisions between grains during transport process while lower flow System-Qin River move grains over short distance at low velocity with little or no change in grain morphometry.

We refer to the genesis of microtextures described by Vos et al. (2014) for an extensive comprehension of features and genesis of microtextures. Silica flowers, silica globules, and silica pellicle were combined into one microtextures, called precipitation since they show many similarities. The common occurrence of arc-shaped steps, linear steps, subparallel linear fractures, conchoidal fractures, and curved grooves was normally associated with glaciogenic sediments (Cowan et al. 2008; Mahaney and Kalm 2000). However, many studies illustrated that conchoidal fractures and arcuate steps were derived from the crystalline source rocks (Armstrong-Altrin et al. 2005; Kenig 2006). Hence, the conchoidal fractures, steps, and curved grooves in Qin River indicated that the

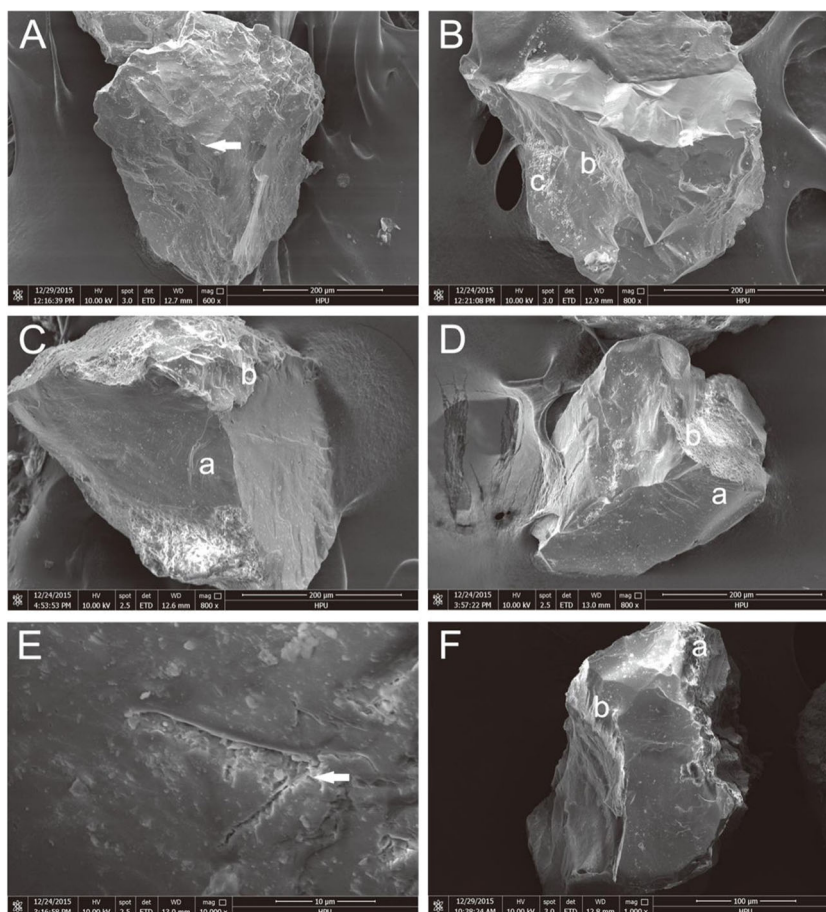
sediment were derived largely from the crystalline rocks since there was no glacial process. The abundance of V-shaped features and abraded features were attributed to the long duration with high intensity of subaqueous agitation and collision (Manickam and Barbaroux 2010).

### Cluster analysis

We analyzed the frequencies of microtextures of 36 samples in different environments from published references and this study. The agglomerative hierarchical clustering (AHC) method was used to ascertain which microtextures tend to coexist (Fig. 6).

It is advised to take into account all microtextures present on a sample when reconstructing the sedimentary history. However, certain microtextures, mainly the mechanical ones, have such abundance on individual grains that they are regarded as diagnostic for specific environment. Transport-induced microtextures could be grouped based on dendrogram representation: (1) cluster A consisted of upturned plates, crescentic percussion, abrasion fatigue, and rounded grain and were inferred to occur predominantly during eolian transport; (2) angular grain, curved grooves, high relief, and deep trough were assigned to cluster B, which were created mainly in

**Fig. 4** Typical surface microstructures for quartz grains from Qin River by scanning electron microscope (SEM). **A** Angular grain with sharp angular features (arrow) and abrasion feature. **B** Angular grain with sharp angular features (a), arc-shaped steps (b), and adhering particles (c). **C** Angular grain with subparallel linear fractures (a), linear steps (b), fracture face, and medium relief. **D** Angular grain with sharp angular features and subparallel linear fractures (a); linear steps, dissolution (b), and high relief. **E** Magnification of V-shaped percussion (arrow). **F** Angular grain with dissolution (a), craters (b), and high relief



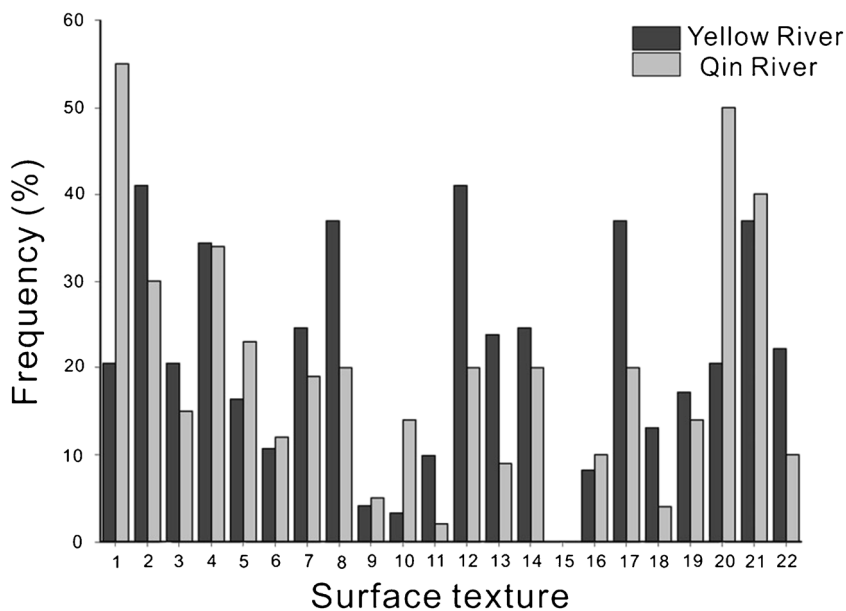
glacial environment or crystallize rock; (3) cluster C were characterized of V-shaped percussion, V-shaped craters, medium relief, scratches, abraded fractures, subangular grain, subparallel linear fractures, linear steps, arc-shaped steps,

conchoidal fractures, dissolution etching, and adhering particles. V-shaped percussion, V-shaped craters, medium relief, scratches, and abraded fractures represent aqueous environment. Our data do not match with previous results precisely. Some authors consider that conchoidal fractures, arc-shaped steps, and linear fractures occur under a wide range of transport process and thus do not have environmental significance (Sweet and Soreghan 2010). A number of references proposed that conchoidal fractures with arcuate steps and edge rounding were microtextures normally associated with glaciogenic space (Cowan et al. 2008; Mahaney and Kalm 2000). Others found that conchoidal fractures and arcuate steps were most frequently found mechanical features among the sand grains derived from crystalline rocks (Armstrong-Altrin et al. 2005; Kenig 2006). From our data, we suggest these features are probably more connected with water transport. In addition, our results are not consistent with dendrogram based on the data of Cenozoic Arctic. The Cenozoic Arctic dataset comprises two main cluster groups where grain characteristics were generally associated with either diagenetic, high-energy fluvial or high-energy costal environment (cluster A) or with high-pressure mechanical origins (cluster B) (Immonen 2013). Cluster A include impact v-pits, fractured planes, low relief, rounded to rounded

**Table 1** Evaluate table

Sample	Fluvial	Marine	Glacial	Eolian	Debris
1	16.0640	15.2413	70.4632	143.3101	69.8221
2	20.7377	17.7349	72.6309	120.8681	76.5078
3	23.5944	31.6926	72.3017	125.7721	46.0350
4	24.7323	33.4340	71.8255	123.9208	44.7427
5	25.8134	34.6981	71.8369	122.2222	44.1842
6	52.9448	71.4640	43.2361	142.7361	25.3242
7	61.7584	44.3180	115.0245	171.7378	114.0481
8	50.4218	37.3792	96.6776	136.6948	108.8960
9	5.4869	15.2401	66.4982	129.7879	61.4253
10	82.2323	101.6175	28.0064	154.0729	66.4116
11	61.2721	81.0983	23.1804	122.8086	47.6643
12	125.8939	129.1063	139.3789	16.8060	136.5950
13	149.2519	154.0123	156.9084	21.3663	152.0982
14	44.4031	61.1430	55.9185	127.0859	15.3866

**Fig. 5** Frequency of occurrence of microtextures on quartz grain from Yellow River and Qin River. 1-angular grain, 2-subangular grain, 3-rounded grain, 4-subparallel linear fractures, 5-linear steps, 6-arc-shaped steps, 7-V-shaped craters, 8-V-shaped percussion, 9-deep trough, 10-curved grooves, 11-upturned plates, 12-scratches, 13-abraded fractures, 14-conchoidal fractures, 15-abrasion fatigue, 16-crescentic percussion, 17-dissolution, 18-precipitation, 19-adhering particles, 20-high relief, 21-medium relief, 22-low relief

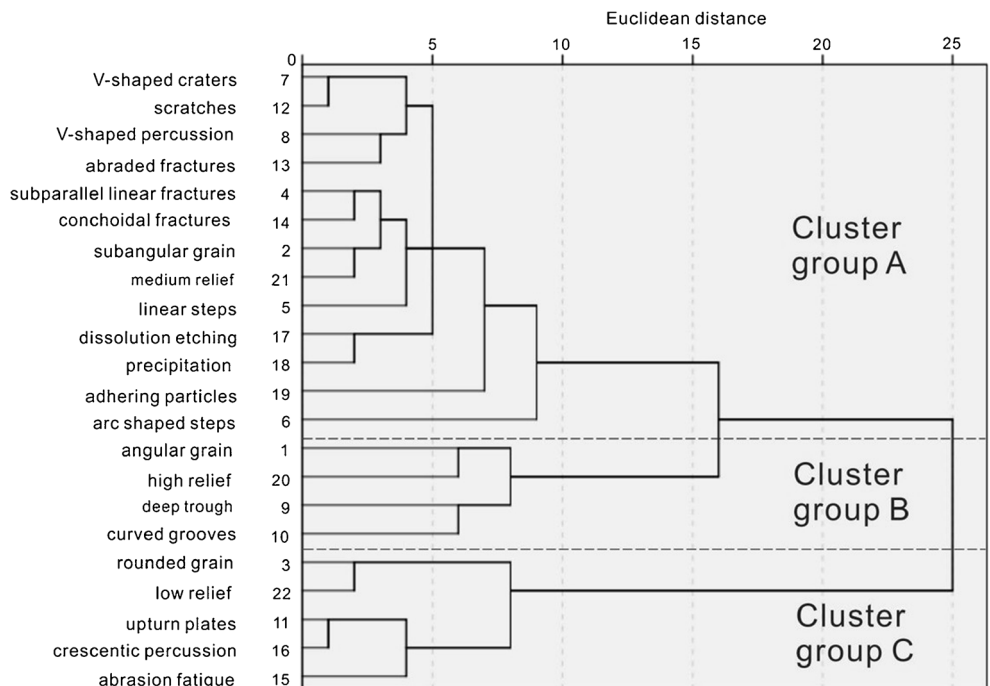


outline, scratches, etching patterns, silica precipitates or adhered particles, subangular to subrounded outline, euhedral silica growth, and grooves, whereas cluster B is characterized layered breakage, medium relief, crystal-shaped mould impressions, conchoidal fractures, high relief, angular to very angular outline, steps, subparallel linear fractures, crescentic gouges, and edge gouges. The slight difference between the results of Immonen and this study can be attributed to the difference of data source where Immonen used the glacial and fluvial data and our data included more different environment.

**Ternary diagram**

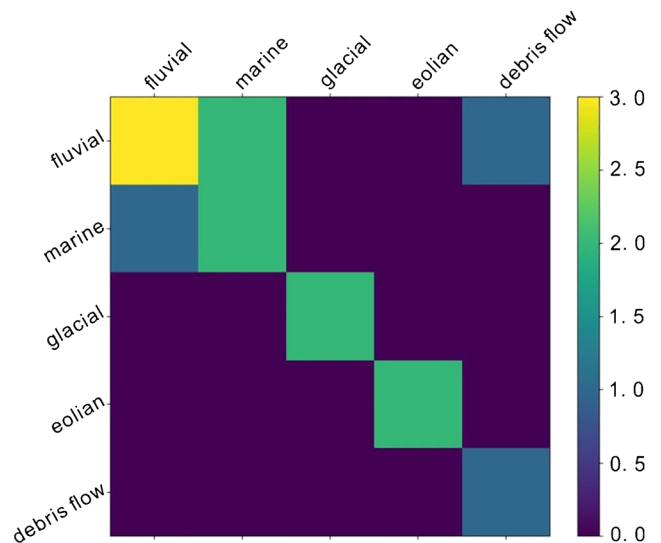
Historically, data on microtextural frequency has been displayed in histogram-type plots (Fig. 5) (Mahaney 1995; Mahaney 2002). However, it is difficult to evaluate significant differences between samples visually, as there are so many microtexture types depicted on these histograms. Therefore, comparison of data to assess transport process is facilitated by grouping microtextures created by similar fracturing process. Accordingly, a potentially useful approach involves classifying mechanically induced microtextures into one of three

**Fig. 6** Dendrogram of collected features and textures in the studied samples. Clustering method is inter group connection, and the interval is cosine



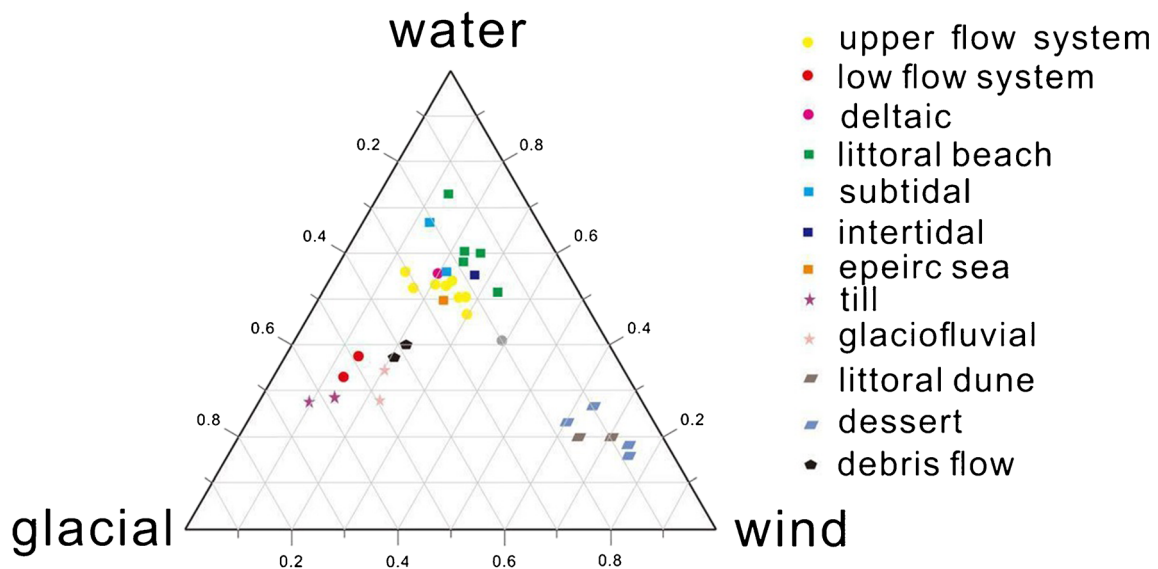
genetic groupings: (1) microtexture features of water transportation, (2) microtexture features of glacial transportation, and (3) microtexture features of wind transportation. These groups can then be plotted on a ternary diagram for semiquantitative intersample comparison (Fig. 7). According to the previous cluster analysis (Fig. 5), 22 microstructures are divided into three components; each point represents a sample, and there are 10–32 quartz particles in each sample, and the ternary diagram is drawn according to the number of microstructure of each particle. Using this approach, we can see that intuitively microtextures of water transport induced are more common in the fluvial, marine, and deltaic facies, whereas microtextures of wind transport induced are more common in the desert and littoral dune. Microtextures of glacial transport induced are common in till and glaciofluvial.

The sand grains of marine are characterized by predominance of straight scratches, V-shaped percussion, smooth surfaces, and subangular to subrounded outlines followed by low and medium relief, adhering particles, and minor etching. The microtextures of water transport induced, such as V-shaped percussion and abrasion features, are higher in the high-energy facies, such as littoral beach and subtidal, than that in the low energy, such as intertidal and epeiric sea. Although marine, high-energy fluvial and deltaic sediments are dominated by V-shaped percussion and straight and curved scratches (Mahaney and Kalm 2000), the quartz particle maturity in the marine is higher than fluvial and deltaic. Therefore, the position of marine in the Fig. 8 is toward right while the fluvial position is toward left. Deltaic is in the middle between fluvial and marine. The fluvial can be divided into



**Fig. 8** Confusion matrix summarizes the results of testing the algorithm. Each column of the matrix represents the instances in a predicted class while each row represents the instances in an actual class. All correct guesses are located in the diagonal of the table, so it is easy to visually the table for errors, as they will be represented by values outside the diagonal. In the 14 test samples, there are 6 fluvial samples, 3 marine samples, 2 glacial samples, 2 eolian samples, and 1 debris flow sample

upper flow system and lower flow system (Mahaney 2002). The observed microtextural assemblages in this study are in line with the upper flow system and lower flow system. The samples of Yellow River exhibit the typical features of saltation process, whereas the mechanical and chemical textures on samples of Qin River confirm the lower flow system. The upper flow system is characterized by V-shaped percussion,



**Fig. 7** Ternary diagram illustrate the relative abundances of microtexture features of water, wind, and glacial. Percentage represents the summation of times that microtextures in their respective group (water, wind, and glacial) were counted relative to the total counts of mechanical microtextures for the entire samples. Each sample consists of 10–32 quartz grains, and the percentage of microtextural occurrence is read from

the corresponding axis. Microtexture features of water apex include V-shaped percussion, V-shaped craters, medium relief, scratches, and abraded fractures; microtexture features of wind apex includes upturned plates, crescentic percussion, abrasion fatigue, and rounded grain; microtexture features of glacial apex includes angular grain, curved grooves, and high relief, and deep trough



dissolution etching, V-shaped craters, precipitation, abraded fractures, and low relief while sharp angular features, high relief, and curved grooves are properties of lower flow system. This finding suggests that upper flow system has a strong reforming ability on quartz grain because of high kinetic energy and long transportation while lower flow system conserves most original features of microtextures. Consequently, the position of upper flow system in Fig. 8 is higher than low flow system. Eolian and glacial environment are most distant, occurring at opposite ends of a spectrum. While there are some microtextural similarities between grains from glacial and glaciofluvial depositional environments, the vast majority of grains from till deposits are and comprised of numerous and distinct microfeatures including angular grain, curved grooves, high relief, and deep trough and a preponderance of conchoidal and linear microfractures. Glaciofluvial grains contain abundant abrasion features and v-shaped percussion cracks that make them very distinct from glacial grains. Accordingly, glaciofluvial sands are intermediate, being closely related to fluvial and, more distantly, to tills. This latter relationship suggests that glacial grain subjected to melt-water transport may be quickly reformed with greater relief and a multitude of v-shaped percussion cracks, the latter is modified to be the definitive recorder of turbulent water transport. Quartz grains from the debris flow facies exhibit a relatively high percentage of conchoidal fractures, having medium relief, and commonly associated with sharp angular features (Sweet and Soreghan 2010), hence, the debris grain in the middle between water apex and glacial apex.

The plot from our work extends the methods of Sweet and Soreghan (2010) and Keiser et al. (2015). Transport-induced microtextures have been grouped based on inferred fracture process into the following: (1) high-stress fractures, consisting of fractures created through sustained high shear stress, such as grooves, deep troughs, and gouges, and are inferred to occur predominantly during glacial transport; (2) percussion fractures, consisting of fractures created by grain-to-grain contact during saltation or traction flow, such as randomly oriented v-shaped cracks and edge rounding; and (3) polygenetic fractures, such as conchoidal fractures, arc-shaped steps, linear steps, and linear fractures that occur under a wide range of transport processes and thus do not have environmental significance. Delineation of high stress, percussion, and polygenetic fracture types demonstrate the quartz grain to be tested similar to which kind of environment or subenvironment. The high-stress fractures and percussion fractures are similar to the apex of microtextures of glacial and water transport induced. The plot of Sweet does not include polygenetic fractures that are present in our plot. However, the plot of Sweet and Soreghan does not include microtexture features of eolian environment, which is not complete to use compared with our plot.

This plot is intriguing, raising the possibility that different environments can be distinguished by microtextures of quartz grain. This study provides the framework for future studies to assess the environment and even subenvironment according to the microtextures. More data systematically collected from different environments are needed to assess the distribution in the plot. Although ternary plot has improved a lot compared with previous plot, there are still some critical points. Because of the polygenetic microtextures, we do not consider conchoidal fractures, steps, and linear fractures when we calculate the apex, leading to lots of useful information. Here, we introduce another method, PCA analysis, which can solve the problem we mentioned above.

### PCA analysis

The main point of PCA is to project high-dimensional samples into low-dimensional space, so that they are in the low-dimensional space to maximize the degree of dispersion, which makes it easier to classify the samples. In this study, 36 samples were divided into two groups, one group is standard specimen, and the other one is test samples. Eleven samples which are chosen for the test were correct for the total 14 evaluate numbers. Here, we make a confusion matrix (Fig. 8) summarizing the results of testing the algorithm for further inspection.

In this confusion matrix, of the 6 actual fluvial samples, the system predicted that there were two marine samples and one debris flow samples. In addition, of the three marine samples, it predicted one was fluvial samples.

Confusion matrix, also known as an error matrix (Stehman 1997), is a specific table layout that allows visualization of the performance of an algorithm in the field of machine learning. We can see from the matrix that the system has trouble distinguishing between marine and fluvial, but provide a clear distinction between glacial and eolian. It can be accounted for the microtextures of fluvial and marine which are induced by water transport predominantly, with a slight difference as the quartz grains in marine are more mature. The results of the PCA with Euclidean distance plot reinforce the findings of raw data, as well as the ternary plot. In contrast, accuracy is not a reliable metric for the real performance of a classified, because it will yield misleading results if the data set is unbalanced. This finding provides unique direct information on similarities among environments. A combination of factors such as the total numbers, climate, and the subjectivity of manual description may have been important in explaining the wide variation range. The problem of this system is the relatively small sample size. In addition, the climate influences the environment, even in the same environment. Cold and hot climates can have a huge impact on the microtextures (Keiser et al. 2015). Therefore, the findings of this study in relation to climate are inconclusive.

## Conclusion

Quartz sand grain microtextures preserve information of the prevailing processes and environment conditions that existed during their formation. According to the microtextures of quartz grain from published papers and from this study on Yellow River and Qin River, transport-induced microtextures can be grouped based on dendrogram representation in 3 clusters, which represent the microtextures induced by wind, water, and glacial transport.

In addition, multiple approaches to data analysis that are beyond visual inspection of raw data histograms, to semiquantitative classification of textures using ternary diagram, as well as quantitative statistical techniques such as the PCA analysis with Euclidean distance, provide quantitatively robust results that greatly enhance the historically qualitative nature of quartz microtextural analysis. In general, we can see that intuitively microtextures of water transport induced are more common in the fluvial, marine, and deltaic facies, whereas we observe that microtextures induced by wind transport are more common in the desert and littoral dune. Microtextures of glacial transport induced are common in till and glaciofluvial. PCA was used to reduce dimensional of standard samples and test samples. The calculated Euclidean distances between samples and environment clusters were correct in 11 samples out of 14, when assigned the shortest distance to the cluster. The correct percentage is 78.57%, which is proved to be a useful method.

In conclusion, the microtexture of quartz grain is a useful tool to discriminate environment using quantitative methods. What needs to be investigated further is the effect of climate on identifying the depositional environment.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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