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ORIGINAL PAPER

# Microtextures on quartz grains in the Kuakata beach, Bangladesh: implications for provenance and depositional environment

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**Abstract**

Microtextures on fine to medium-grained quartz grains (65–500 μm) from three sections, i.e., Laboni, Kuakata, and Jhauban points of the Kuakata beach area, Bangladesh, were examined by a scanning electron microscope (SEM) to determine the transport history, provenance, depositional environment, and paleoclimate. Thirty microtextures were observed on 180 quartz grains, which were subsequently classified as mechanical (20 features), chemical (5 features), and combined mechanical and chemical (5 features) origins. The abundance of sub-rounded to rounded quartz grains with smooth outlines, V-shaped pits, straight or curved grooves, crescent-shaped features and straight or arcuate steps, indicates that the quartz grains experienced long-distance transport through fluvial environment (e.g., Himalayan sediments). The angular to sub-angular quartz grains with straight or curved grooves, straight steps, and adhering particles inferred that they were probably derived from adjacent landmasses (e.g., Chittagong-Tripura Folded Belt and/or Indo-Burman Ranges). The well-rounded outlines, low relief with dish-shaped depressions, mechanically upturned plates, and arcuate steps were also observed, indicating aeolian processes in shoreface or beach environment. Etching, solution/irregular pits, and differential relief observed in the quartz grains indicate a subaqueous collision in fluvial and nearshore environments.

**Keywords** Quartz grain morphology · Microtexture · Scanning electron microscope · Beach sediments · Bengal Basin · Bangladesh

## Introduction

Microtexture on sand grains, examined by SEM, has often been used to infer the depositional environment, paleoclimate, and mode of transport mechanisms (Krinsley and Doornkamp 1973; Mahaney 2002; Madhavaraju et al. 2006; Kirshner and Anderson 2011; Marshall et al. 2012; Costa et al. 2013; Armstrong-Altrin and Natalhy-Pineda 2014; Hossain et al. 2014; Vos et al. 2014; Kalińska-Nartiša et al. 2017a; Křížek et al. 2017; Chmielowska and Woronko 2019). The origin of microtextures on quartz grain surfaces mainly depends on glacial, glaciofluvial, fluvial, periglacial, aqueous, and aeolian landform processes in the earth surface (Mahaney 2002; Madhavaraju et al. 2006; Hossain et al. 2014; St John et al. 2015; Woronko 2016; Kalińska-Nartiša et al. 2017a; Szerakowska et al. 2018). The frequency of quartz grain morphological features developed in fluvial regime is normally associated with transport distance, energy condition, and sedimentation rate in the stream (Mahaney 2002). Mechanical microtextures are common and frequently developed on quartz

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grain surfaces during transport in glacial systems, as well as in fluvial and aeolian environments (Doornkamp and Krinsley 1971; Mahaney et al. 2001; Mahaney 2002; Sweet and Soreghan 2010; Costa et al. 2013; Kalińska-Nartiša et al. 2017b). Microtextures such as conchoidal fractures, parallel striations, straight or curved grooves, crescent-shaped features, straight or arcuate steps represent mechanical origin, whereas fracture plates/planes and adhering particles can indicate the combination of both mechanical and chemical processes (Krinsley and Doornkamp 1973; Krinsley and McCoy 1977; Helland et al. 1997; Mahaney 2002; Madhavaraju et al. 2006; Kirshner and Anderson 2011; Hossain et al. 2014; St John et al. 2015; Woronko 2016; Křížek et al. 2017). Edge rounding, V-shaped pits, straight or curved grooves, and other impact features are originated by fluvial transport pathways (Krinsley and Donahue 1968; Madhavaraju et al. 2009; Costa et al. 2013; Kalińska-Nartiša et al. 2017a; Kalińska-Nartiša et al. 2018; Szerakowska et al. 2018). Quartz grains with angular outlines, V-shaped pits (Vs), high relief, deep grooves, and striations are typically of glacial environment (Mahaney 2002; Vos et al. 2014), while precipitation and dissolution features represent glaciofluvial environment (Bull and Morgan 2006; Křížek et al. 2017). Etching pits, silica precipitation, and quartz overgrowth microtextures observed on sand grains may derive by chemical and mechanical origins (Mahaney 2002; Madhavaraju et al. 2006; Armstrong-Altrin and Natalhy-Pineda 2014; Křížek et al. 2017). Crystalline overgrowths may develop in sand grains during diagenesis after burial (Vos et al. 2014). Chattermark trails, a glacial origin microtexture, typically develop in quartz grains in tropical climatic condition (Peterknecht and Tietz 2011).

The Bengal Basin is placed on the eastern part of the Indian subcontinent, which occupies the entire Bangladesh, part of India and Myanmar (Fig. 1a). This basin lies at the confluence of the Ganges, Brahmaputra, and Meghna rivers (GBM), originated from the western and eastern Himalayan syntaxes and the Indo-Burman Ranges. The whole GBM drainage system together carries enormous volume of sediments each year from the Himalaya-Tibetan Plateau and discharges into the Bay of Bengal (Hossain et al. 2010; Hossain 2019). These clastic sediments experienced numerous episodes of glacial, glaciofluvial, fluvial, periglacial and aeolian conditions and transformed by varied monsoon climates. Therefore, the Bengal Basin sediments are most important for geoscientists worldwide to investigate sediment sources, depositional environments, climate patterns, and transportation history. The Bengal Basin with its subaerial delta and prodelta has been made by the seaward progradation of the GBM systems (Einsele et al. 1996; Hossain et al. 2014). The Kuakata beach area is in the southern part of Bangladesh (Fig. 1a), bounded to the east by Gangamati reserve forest and to the west by Sundarbans mangrove forest, which is about 18 km long and 2 km wide. The Galachipa and Kazal are the two major rivers (tributaries of the Meghna River) flowing from the northeastern part of Bangladesh and feeding sediments near the Kuakata beach area (Fig. 1b). The terrane east of the examined beach site comprises predominantly of sandstone, shale/mudstone, and siltstone of Miocene age (Garzanti et al. 2013).

Textural properties of Cox's Bazar beach sands and Gondwana sediments from the Bengal Basin, Bangladesh, have been studied only by very few authors (Mitra and Ahmed 1990; Rahman and Ahmed 1996; Hossain et al. 2014). Recently, geochemical composition of sediments from the Cox's Bazar and Kuakata beach areas was investigated by Hossain et al. (2018), to infer provenance. They concluded that the beach sediments of Bangladesh were derived largely from the felsic source rocks of the rising Himalaya-Tibetan Plateau and the Indo-Burman Ranges. However, none of these studies utilize microtextures on quartz grains from the Kuakata beach area of southern Bangladesh to examine sediment provenance. In this study, we discussed the microtextures on quartz grains collected from the Kuakata beach area, Bangladesh. The objective of this study is to infer the provenance and depositional environment of sediments based on the type of quartz grain microtextures.

## Study area

In this study, we selected three beach sites of the Patuakhali district, southern part of the Bengal Basin of Bangladesh (Fig. 1). The beach sites are situated between longitudes 90°03′E to 90°17′E and latitudes 21°47′N to 21°53′N. The Ganges and Brahmaputra rivers transport large volume of eroded terrigenous materials from the Himalayan Orogeny and discharges to the coastal region of Bangladesh (Hossain et al. 2010). Rock types in the Himalaya-Tibetan Plateau are sedimentary/metasedimentary rocks, low- to high-grade metamorphic, crystalline, and carbonate rocks (Heroy et al. 2003; Hossain et al. 2018). However, the Meghna River drains from the northeastern Himalayan syntaxes and western part of the Indo-Burman Ranges (Hossain 2019), where flysch- and molasse-type sediments with tiny limestones, sandstones, and shales are omnipresent (Allen et al. 2008; Hossain 2019). The Ganges and Brahmaputra rivers join with the Meghna River at Chandpur district making the Ganges-Brahmaputra-Meghna river system, carrying mixed sediments from its upper reaches to the Bay of Bengal (Fig. 1). The rivers feeding sediments to the investigated beach sites are the Galachipa and Kazal rivers. These two rivers originate from the lower Meghna River and deliver sediments to the coastal vicinity of the southern Bengal Basin (Hossain et al. 2018). The beach area is closely related with the frequent atmospheric circulation and passage of enormous cyclones over the Bay of Bengal. The storm surge disperses coastal environments and likely redistributing sediments in the beach areas. Several sedimentary features of different types are developed in the Kuakata beach area, such as sand dunes and ripple marks. The Kuakata beach consists of a flat and wide

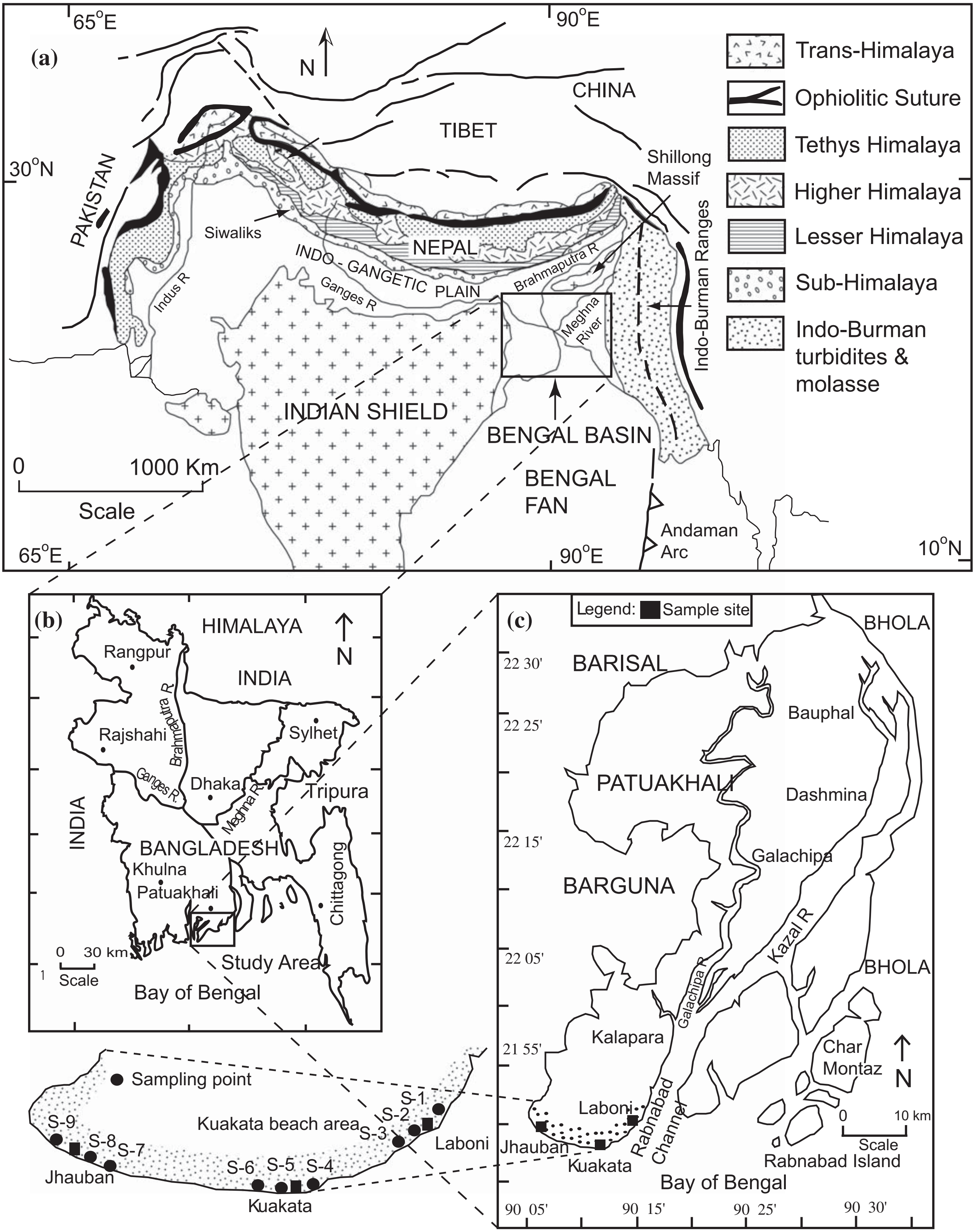


**Fig. 1** **a** Simplified map of the Himalayas and surrounding regions. **b** General map of Bangladesh and adjoining areas. **c** Location map of the study area showing sample sites from the Kuakata beach, Bangladesh (modified after Hossain et al. 2018)

backshore, broad berm, wind ripple, and gentle beach face. Swash process is common in this area. The foreshore region of the beach encompasses a steep slope, and it extends from low water level to the usual high tide level. However, the nearshore zone of the studied beach is always beneath the seawater and retains wave ripples and longshore bars.

## Material and methods

Nine sediment samples (each ~100 g) were collected from the Kuakata beach, southern part of the Bengal Basin, Bangladesh, along transects at regular interval of approximately 500 m. The sampling sites are shown in Fig. 1. To remove carbonate coatings and ferruginous materials, ~ 20 g of beach sediment was treated with cold 12% HCl, and subsequently washed with distilled water. The cleaned samples were then soaked with 30% $H_2O_2$ to eliminate organic substances. Stannous chloride solution was also added to completely remove adhering iron coatings from the samples. After removal of the adhering materials, the sand grains were washed with distilled water and dried at room temperature. For SEM study, 20 quartz grains (200–400 μm) were hand-picked from each sample using a binocular microscope (Krinsley and Doornkamp 1973; Krinsley and McCoy 1977; Higgs 1979). The selected quartz grains were placed on SEM stubs, a JFC-1100 fine gold coating apparatus, and then examined with JEOL-JSM-6360LV SEM at the Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México (UNAM), Mexico. The microtextures were identified using magnifications between × 100 and × 750 and between × 1000 and × 15,000, respectively by following the methodology of Higgs (1979) and Krinsley and Doornkamp (1973). The examined microtextures were subdivided as (i) abundant (A, microtextures identified in > 76% of grains), (ii) common (C, 51–75%), (iii) sparse (S, 26–50%), (iv) rare (R, 1–25%), and (v) not observed (NO) (Mahaney 2002; Kalińska-Nartiša et al. 2017a, b).

The mineralogical composition of seven samples from the Kuakata beach was identified at Universidad Nacional Autónoma de México (UNAM), Mexico, using a PHILIPS XL-30 scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS). The methodology followed is similar as explained in detail in Armstrong-Altrin et al. (2018, 2019). The composition of sand grains obtained by SEM-EDS is listed in the Supplementary Tables S1 and S2.

## Results

### Mineralogy

The SEM-EDS data shows that the Kuakata beach sands are characterized by dominantly quartz (Si), feldspar (K, and Na), calcite (Ca), and magnetite (Fe) minerals (Supplementary Tables S1 and S2). The Laboni beach point is enriched with quartz, plagioclase, and Fe-bearing minerals, whereas quartz with K-feldspar is more common in the Kuakata point.

### Microtextures on quartz grains

Surface microtextures on quartz grains from the Kuakata beach area, Bangladesh, are listed in Table 1. In the present study, totally, we identified 30 microtextures on the quartz grains and are classified into three groups according to their mode of origin. Among them, 20 microtextures are of mechanical origin, five are chemical dissolution/precipitation origin, and five are combined mechanical and chemical origin (Table 1; Figs. 2, 3, and 4). The mechanical microtextures consist of small, medium, and large pits, conchoidal fractures of varying size; straight and arcuate steps; upturn plates; straight and curved scratches; V-shaped pits (Vs); angular, sub-angular, sub-rounded, and rounded outlines; and smooth grain surfaces. The chemical microtextures include etched surface, solution pits, and silica globules and silica flowers, and the combined mechanical and chemical microtextures are relief, fracture plates/planes, and adhering particles.

Quartz grains with rounded shape and low relief range from sparse to abundant and their total occurrence varies from 70 to 90%, 70 to 95%, and 60 to 85% in the Laboni, Kuakata, and Jhauban points, respectively. Grains with medium relief are sparse to common in the Laboni, Kuakata, and Jhauban points (70%, 85%, and 75%, respectively), but high relief with angular shapes are rarely identified in Jhauban point (~ 5%).

### Mechanical microtextures

Quartz grains from the Kuakata beach area show diverse categories of collision pits (Fig. 3; Table 1). Small and medium pits were omnipresent in the investigated samples, whereas large pits were sparse or rarely present on grains from the Jhauban point.

Like irregular pits, different sizes of conchoidal fractures (small, medium and large) were also present in the beach sand (Figs. 2 and 3), of which small to medium conchoidal fractures were common and more than 75% was identified in the Laboni point. However, conchoidal fractures with straight and arcuate steps were abundant in Jhauban (> 60%) and sparse to common in Laboni and Kuakata points (Figs. 3 and 4). Mechanically upturned plates and V-shaped pits were either common or sparse in all the beach point, with higher frequency (65–85%) in the Kuakata beach point. Chattermark trails were observed only in few grains, and parallel striations were present in small amount mostly below 10% of the microtextures. Similarly, straight and curved scratches were common to sparse in the entire sand grains, and high abundance was

**Table 1** Surface microtextures on the quartz sand grains identified by scanning electron microscope (SEM) from the Kuakata beach point, Bangladesh

| Microtextures | Laboni | Kuakata | Jhauban | Origin |
|---|---|---|---|---|
| Small pits | A | A | C | Mechanical |
| Medium pits | C | C | A | Mechanical |
| Large pits | S | R | A | Mechanical |
| Small conchoidal fractures | A | A | C | Mechanical |
| Medium conchoidal fractures | C | C | A | Mechanical |
| Large conchoidal fractures | A | C | A | Mechanical |
| Straight steps | C | S | S | Mechanical |
| Arcuate steps | C | C | S | Mechanical |
| Upturned plates | S | R | C | Mechanical |
| V-shaped patterns | A | C | S | Mechanical |
| Chatter marks | NO | R | R | Mechanical |
| Parallel striations | C | S | C | Mechanical |
| Meandering ridges | R | R | NO | Mechanical |
| Straight scratches | C | C | A | Mechanical |
| Curved scratches | A | S | C | Mechanical |
| Angular outline | S | R | A | Mechanical |
| Sub-angular outline | S | C | A | Mechanical |
| Sub-rounded outline | A | S | C | Mechanical |
| Rounded outline | A | S | S | Mechanical |
| Smooth surfaces | A | C | S | Mechanical |
| Solution pits | C | C | S | Chemical dissolution |
| Etching | S | C | S | Chemical dissolution |
| Silica globules | NO | R | S | Chemical precipitation |
| Silica flowers | S | R | NO | Chemical precipitation |
| Quartz overgrowth | R | NO | R | Chemical precipitation |
| Fractured plates/planes | S | C | R | Combined mechanical and chemical |
| Low relief | R | C | S | Combined mechanical and chemical |
| Medium relief | S | R | C | Combined mechanical and chemical |
| High relief | S | S | C | Combined mechanical and chemical |
| Adhering particles | S | C | A | Combined mechanical and chemical |

*A* abundant (> 76%), *C* common (51–75%), *S* sparse (26–50%), *R* rare (1–25%), *NO* not observed

identified in Jhauban beach with a frequency varied between 0.5 and 100 μm (Table 1). Rounded and sub-rounded outlines were common on quartz grains from Laboni and Kuakata beach locations (Figs. 2 and 3), whereas angular and sub-angular outlines were sparse and common in Jhauban beach points. Quartz grains with smooth surfaces were not common.

## Chemical microtextures

Microtextures on quartz grains resulting from chemical dissolution/precipitation processes were identified in all the quartz grains. Solution pits and etched surfaces were common among the chemical microtextures identified (Figs. 2, 3, and 4), which were observed in most quartz grains with a frequency of 50–80% and 55–90% in the Kuakata and Laboni beach locations, respectively. Microtextures of chemical precipitation origin such as silica globules, silica flowers, and quartz overgrowths were rare in the quartz grains.

## Combined mechanical and chemical microtextures

The distribution of combined mechanical and chemical microtextures of fracture plates/planes in the quartz grains was sparse (Table 1). Low, medium, and high relief were also observed in the quartz grains. High relief was abundant (> 75%) in the Laboni beach point but rare in the Kuakata beach point and occasionally present in the Jhauban beach sands. Adhering particles were common in the Laboni and Kuakata beach points whereas rare in the Jhauban beach point.

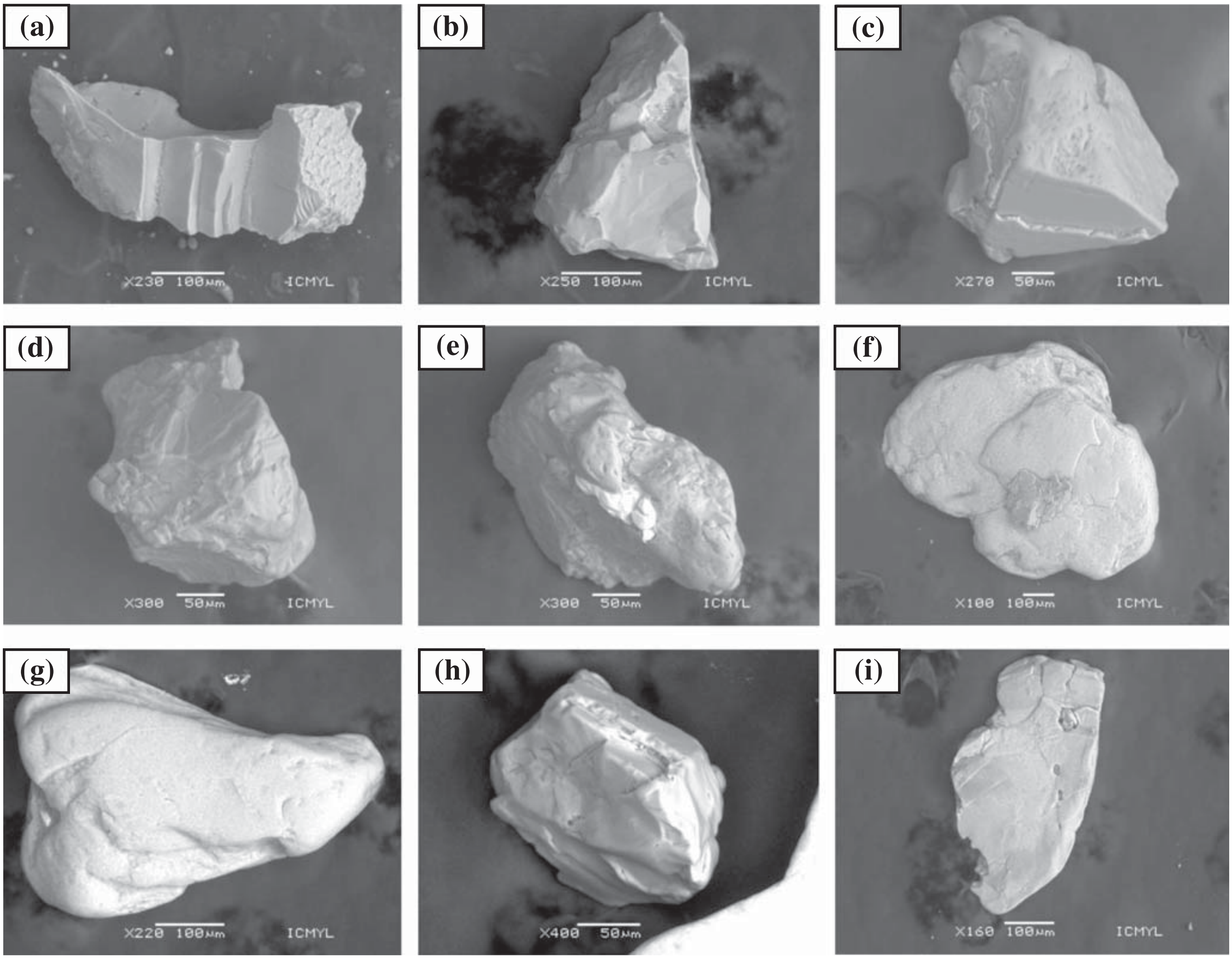


**Fig. 2** Surface microtextures on quartz grains identified by SEM from the Kuakata beach area, Bangladesh. **a** Angular quartz grain displaying sharp-edge, large conchoidal fractures, deep grooves, V-shaped patterns, and straight and arcuate steps. **b** Sub-angular quartz grain showing many small fracturing, parallel striations, V-shaped pits, dish-shaped depressions, solution pits, and adhering particles. **c** Quartz grain with fracture plates/planes, solution pits, curved striations, and small and medium conchoidal fractures. **d** Quartz grain edge shows edge rounding, small to large conchoidal fractures, low to medium/high relief, and V-shaped pits. **e** Quartz grain showing smooth surface feature with adhering particles, silica precipitation, and arcuate steps. **f** Sub-rounded quartz grain demonstrating small to medium pits, rounded outlines, mechanically upturned plates, and crescentic grooves. **g** Quartz grain showing edge rounding, mechanically upturned plates, curved grooves, crescentic features, smooth surfaces, small pits, and curved striation. **h** Quartz grain displaying straight and curved scratches, conchoidal fractures, etching, and small adhering particles. **i** Sand grain showing smooth surface, edge rounding, straight/curved striation, conchoidal fractures, and adhering particles

## Discussion

### Provenance and depositional environment

Microtextures on quartz grains from the Kuakata beach area display diverse categories, indicating that the sediments were experienced multiple sedimentary environments. The intensity of roundness of the quartz grains mostly depends on the residence time in a specific environment, grain stability, and mode of transport (Costa et al. 2013; Vos et al. 2014; Kalińska-Nartiša et al. 2017b; Woronko et al. 2017). In an aeolian environment, wind action tends to produce rounded to well-rounded quartz grains, low relief with dish-shaped depressions, mechanically upturned plates, and arcuate and circular surface features (Krinsley and McCoy 1978; Marshall et al. 2012; Kalińska-Nartiša et al. 2017a; Szerakowska et al. 2018; Chmielowska and Woronko 2019). Accordingly, rounded grains with low relief may have been derived by onshore transport in coastal environments or due to the effect of aeolian saltation (Sweet and Soreghan 2010; Vos et al. 2014). Moderately rounded sand grains with smooth edges and variable protrusions are characteristic features of aeolian transport and deposition in beach/dune systems (Hossain et al. 2014). Well-rounded quartz grains with clouded surface features may also be inherited from fluvial settings (Kalińska-Nartiša et al. 2017a) and/or exposed to chemical weathering in a high-energy aquatic condition (Křížek et al.

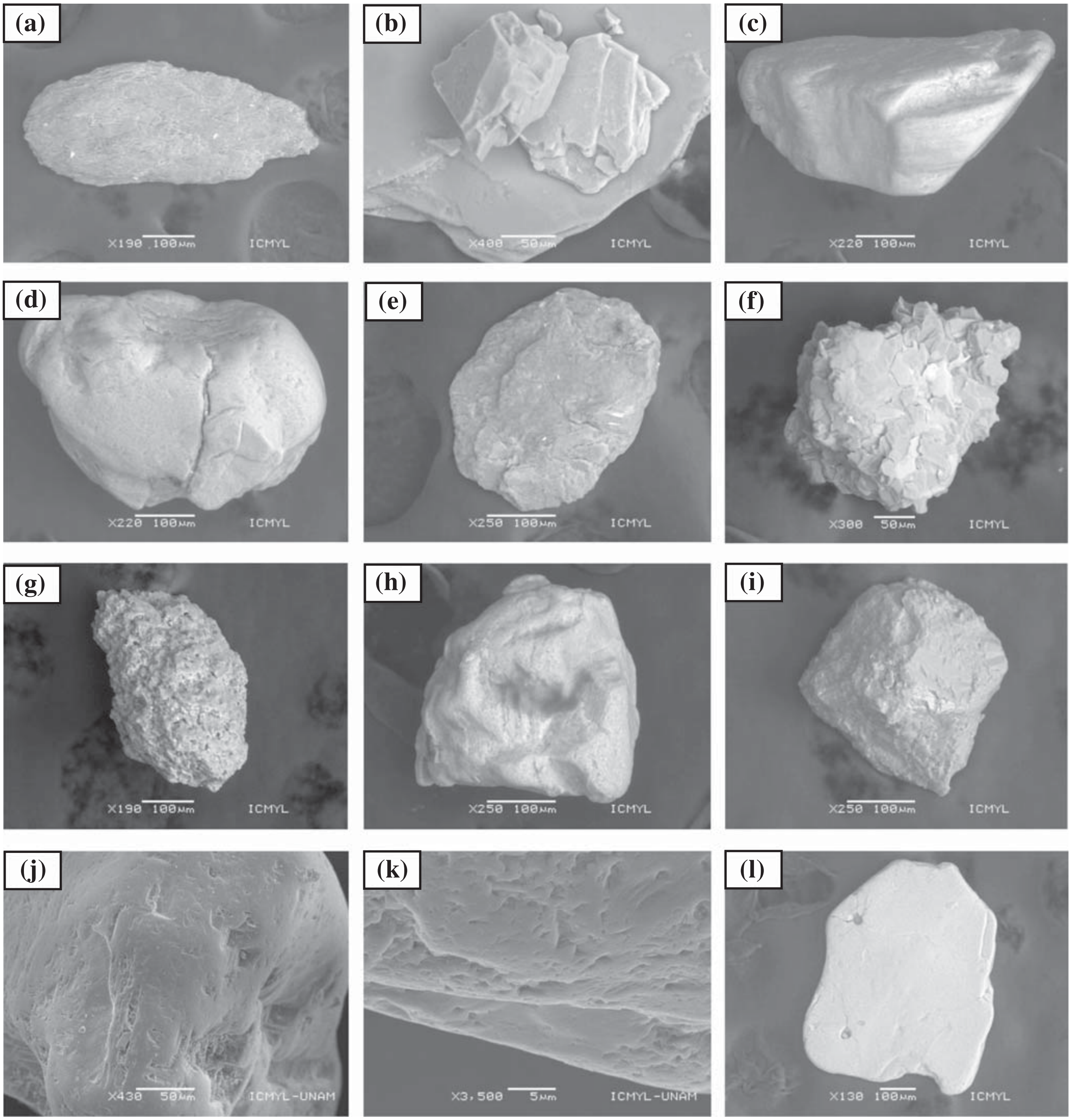


**Fig. 3** Surface microtextures on quartz grains identified by SEM from the Kuakata beach area, Bangladesh. **a** Quartz grain displaying straight and arcuate steps, solution/V-shaped pits, different relief, and adhering particles. **b** Quartz grain with adhering particles, conchoidal fractures, deep grooves, and low to medium relief. **c** Quartz grain showing parallel and curved striations with many adhering particles, solution pits, sheet-like surface appearance, and silica precipitation. **d** Sub-rounded quartz grain with edge rounding, meandering ridges, small to large conchoidal fractures, different relief, V-shaped pits, and parallel striation. **e** Quartz grain displaying sub-angular to sub-rounded outlines, etching, and crescentic marks. **f** Sub-angular quartz grain showing fracture plates/planes, V-shaped patterns, and angular outlines. **g** Quartz grain demonstrating solution pits, low to medium relief, and adhering particles. **h** Sub-rounded quartz grain with straight and curved scratches, medium to high relief, small solution pits, smooth outlines, and dull surface. **i** Quartz grain representing mechanically upturned plates, low relief, small pits, V-shaped patterns, curved scratches and sub-rounded outlines. **j** V-shaped pits with adhering particles. **k** Small and large size V-shaped pits, linear pits, and curved scratches. **l** Large-size pits with precipitation

2017). The most common microtextures on the quartz grains are edge rounding (sub-rounded) with highest frequency, demonstrating both fluvial and aeolian origin. Quartz grains with rounded and sub-rounded edges and polished surface

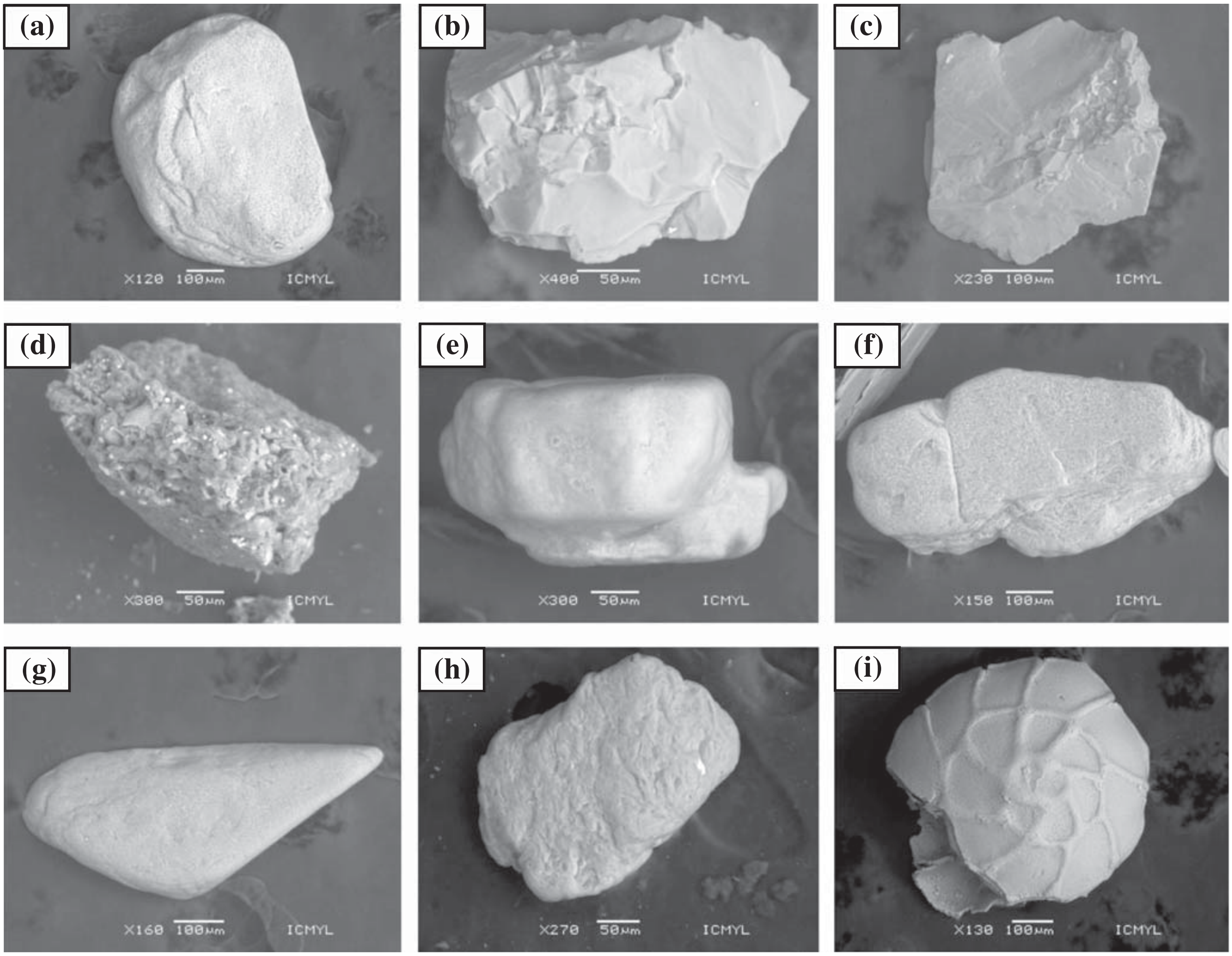


**Fig. 4** Surface microtextures on quartz grains identified by SEM from the Kuakata beach area, Bangladesh. **a** Quartz grain displaying edge rounding, smooth surfaces, and dish-shaped depressions. **b** Sub-angular quartz grain with medium relief, conchoidal fractures, chattermark features, and straight and arcuate steps. **c** Quartz grain representing conchoidal fractures, medium to high relief, silica globules, V-shaped patterns, and adhering particles. **d** Quartz grain demonstrating solution pits, cavities, irregular hollows, quartz precipitation, and conchoidal fractures. **e** Quartz grain showing edge rounding, smooth surface feature, circular solution pits, and straight scratches. **f** Angular quartz grain with smooth outlines, mechanically upturned plates, low relief, and small pits. **g** Angular quartz grain display edge rounding, pits, dull surface and crescentic marks. **h** Quartz grain showing many adhering particles, fracture planes, and small pits. **i** Skeleton of benthic organism

microtextures were common in Laboni and Kuakata beach points (Figs. 2 and 3). Mahaney et al. (2004) reported that smooth surfaces on the quartz grains occurred due to post-depositional changes during sedimentation. The sub-rounded to well-rounded quartz grains in the three beach points probably indicate long-distance transportation via Ganges and Brahmaputra rivers (e.g., Himalayas). Conversely, angular to sub-angular outlines on the quartz grains with straight and arcuate steps are the product of short-range transport pathways and rapid sedimentation burial system (Madhavaraju et al. 2006; Hossain et al. 2014). Angular and sub-angular outlines on quartz grains were sparse and common in Jhauban beach (Fig. 4) and comparatively little lower abundances in the Laboni and Kuakata beach points (Figs. 2 and 3). Although most of the quartz grain microtextures identified in the beach locations were of fluvial and/or aeolian origin, angular quartz grains indicate that they were derived from nearby highland areas (e.g., Chittagong-Tripura Folded Belt or Indo-Burman Ranges).

Additionally, V-shaped pits on quartz grains may have been developed in fluvial settings, which are subjected to agitation in subaqueous or littoral environments during long transport or sediment recycling (Krinsley and Doornkamp 1973; Mahaney and Kalm 2000). In general, triangular depressions have diameter up to 5 mμ, an average depth of 0.1 mμ, and density difference between 1 and 6 individuals per $m\mu^2$ (Krinsley and Donahue 1968; Higgs 1979; Krinsley and Margolis 1971; Vos et al. 2014). The asymmetrical distribution of V-shaped pits and fractures on quartz grains were primarily developed in medium to high-energy subaqueous environments owing to the abrasion over frequent transport cycles (Margolis and Krinsley 1974; Armstrong-Altrin and Natalhy-Pineda 2014). High-collision fractures and V-shaped pits in quartz grains are probably generated through transportation in glacial settings (Hossain et al. 2014; Kalińska-Nartiša et al. 2018). However, percussion fractures on quartz grains may also be produced by impacts in high-energy subaqueous, glaciofluvial, and/or marine regime (Sweet and Soreghan 2010; Vos et al. 2014; Kalińska-Nartiša et al. 2018). Quartz grains with straight and curved grooves, deep pits, high relief, and crescentic gouges can occur because of constant high shear stress processes (Mahaney and Kalm 2000; Mahaney 2002; Sweet and Soreghan 2010; Vos et al. 2014; Szerakowska et al. 2018). However, V-shaped pits with clear straight and curved scratches were abundant in littoral, high energetic fluvial and deltaic grains (Mahaney and Kalm 2000; Mahaney 2002; Kalińska-Nartiša et al. 2018). Such features were common to sparse in the quartz grains studied from the Kuakata beach (Table 1), which is due to the nearby fluvial and deltaic systems with vigorous energy impact during transportation. The Himalayan glaciers are the main source of the Ganges-Brahmaputra Rivers, and these rivers transport sediments from the Himalayan orogeny to the Bengal Basin (Hossain et al. 2010). The Galachipa and Kazal rivers transport sediments from downward portion of the GBM to the investigated beach points (Fig. 1). Parallel striations, straight steps, and edge abrasion microtextures were common and sparse in the studied quartz grains (Figs. 2, 3, and 4), which are characteristic features of glacial environments (Krinsley and Donahue 1968; Křížek et al. 2017). Randomly oriented V-shaped pits of different size and depth on quartz grain surfaces could probably indicate their transport in a high-energy subaqueous environment (Mahaney and Kalm 2000; Mahaney 2002; Madhavaraju et al. 2006). Hence, V-shaped pits with various sizes identified in the investigated quartz grains provide evidence for high-energy subaqueous environments (Figs. 2, 3, and 4).

Quartz grains in the Kuakata beach display different types of pits (Table 1). These pits can be ascribed from grain to grain collision processes associated with diverse sedimentary settings like aeolian and/or beach environments (Higgs 1979; Armstrong-Altrin et al. 2005; Madhavaraju et al. 2006). Small, medium, and large pits were widely distributed in quartz grains from the Kuakata beach point. Small and medium pits were abundant microtextures in the Laboni and Kuakata beach points, whereas large pits were sparse in the Jhauban beach (Table 1). Irregular pits on quartz grains also show differential relief (Fig. 4), suggesting a distinct impact by subaqueous collision in fluvial or nearshore environments (Rajganapathi et al. 2013). This observation, however, indicates typically fluvial environment, which is most fitted from aeolian/wave input in the Jhauban beach point.

Conchoidal fractures with straight and arcuate steps were common in the quartz grains (Figs. 2, 3, and 4); few grains are identified with deep troughs/grooves suggesting their association with low-velocity collisions and experienced in a relatively short distance transport (Mahaney and Kalm 1995) and thus indicating its possible derivation from crystalline source rocks (Krinsley and Smith 1981; Armstrong-Altrin and Natalhy-Pineda 2014). Accordingly, these surface features were also made by high-energy subaqueous and/or littoral environments due to abrasion (Cardona et al. 1997; Armstrong-Altrin et al. 2005; Hossain et al. 2014). The crystalline rocks are exposed in the Shillong Massif, Mikir Massif, and Himalaya-Tibetan Plateau (DeCelles et al. 1998; Heroy et al. 2003; Hossain et al. 2010). Detrital sediments in the Bengal basin, Bangladesh, were primarily derived from rapid erosion and uplift of the Himalayan orogeny and Indo-Burman Ranges, subsequently transported by the Ganges, Brahmaputra, and Meghna rivers (Einsele et al. 1996; Allen et al. 2008; Hossain et al. 2010). Heavy minerals of the Inani beach, Cox's Bazar, Bangladesh were derived from the crystalline and sedimentary rocks of the rising Himalayas, Rajmahal hills, Shillong Massif, and Indo-Burman Ranges (Rahman et al. 2008; Hossain et al. 2014). Thus, varied conchoidal fractures with straight and arcuate steps and edge rounding of the Kuakata beach quartz grains can also be attributed to mechanical breakdown from crystalline rocks. Crystalline rocks are well-exposed in the Shillong Massif and Rajmahal hill region; therefore, influx of relief-developed quartz grains could be the result of erosion of crystalline rocks and transported by rivers and streams to the studied beach points. Chattermark trails were detected only in few quartz grains, but parallel striations were common and sparse (Table 1), which suggest the mobilization of quartz grains under glacial conditions associated with wet tropical climate (Peterknecht and Tietz 2011; Armstrong-Altrin and Natalhy-Pineda 2014). Mechanically upturned plates/planes, straight scratches, and arcuate and circular surface features with polished edge were common in all the quartz grains (Figs. 2, 3, and 4), suggesting that these quartz grains experienced multiple transport histories and origin. Meandering ridge was also observed on some quartz grains, indicating a long-distance transport in fluvial (Křížek et al. 2017) or glacial environment (Higgs 1979).

The distributions of chemical dissolution features (e.g., circular pits and etching) are sparse and common in all the three beach locations (Table 1). These microtextures on quartz grains are ubiquitous in global fluvial settings (Kalińska-Nartiša et al. 2017a), but it has also been reported in marine environment (Higgs 1979; Madhavaraju et al. 2006). Chemical precipitation features such as silica globules and silica flowers were identified in some grains from the Kuakata beach. The silica globules were developed in low-energy aqueous environments with grain contact in silica-supersaturated fluids (Madhavaraju et al. 2006; Křížek et al. 2017), and the silica flowers may develop by the coalescence of silica globules through continuous precipitation of silica (Vos et al. 2014). Quartz crystal overgrowths, a chemical precipitation feature, are typical indicators of burial diagenesis (Mahaney 2002; Sweet and Soreghan 2010; Vos et al. 2014), which has also been observed in the investigated quartz grains.

Quartz grain from the Kuakata beach area shows combined mechanical and chemical microtextures of varying frequency (Table 1). Fracture plates/planes were common in the Jhauban point but sparse and rare in the Laboni and Kuakata points (Figs. 2 and 3). Abundances of these microtextures on quartz grains could have probably originated by wind/wave action during transportation in the fluvial regime (Armstrong-Altrin and Natalhy-Pineda 2014; Hossain et al. 2014). High relief is common on quartz grains in the Laboni beach point whereas sparse to rare in the Kuakata and Jhauban beach points. However, few grains are identified with low to medium relief. High relief is attributed to its origin from first-cycle weathered grains or by glacial action (Vos et al. 2014). Debris-flow environments are also able to generate high relief on the sand grains (Sweet and Soreghan 2010). Low- and medium-relief microtextures are common in diagenetic environments (Vos et al. 2014) and shoreface zone (Kairo et al. 1993; Sweet and Soreghan 2010). Medium- and high-relief microtextures on quartz grains are abundant in the Jhauban section indicating glacial/debris-flow settings, and quartz grains with low relief could probably be initiated in shoreface conditions. Adhering particles have been developed in both fracture planes and smooth surfaces on the quartz grains (Figs. 2, 3, and 4) representing subaqueous environment with high capability to reform crystals and/or the sign of glacial grinding (Smalley 1966; Krinsley and Smalley 1973; Křížek et al. 2017). Dull appearance on quartz grain surface has been delineated to subsequent silica precipitation, and abrasion was characterized by smooth surfaces with tiny V-shaped pits on convex parts of the grains (Kalińska-Nartiša et al. 2017a). Such surface features were omnipresent in the studied grains and suggesting fluvial environment (Table 1). Benthic organisms were also identified in the studied samples (Fig. 4), which indicates high-energy littoral environment (Armstrong-Altrin and Natalhy-Pineda 2014).

### Impact of fluvial environment on quartz grains

Quartz sand grains representing the fluvial environments have a smooth surface with diverse micro-irregularities due to the impact of chemical etching and high-energy grain-to-grain collision (Krinsley and Doornkamp 1973; Mahaney 2002). However, in the low-energy fluvial environment, V-shaped pits and crescentic gouges are common, while V-shaped percussion cracks developed by impacts in high-energy subaqueous conditions are common in the littoral zone, braided river, and/or glaciofluvial deposits (Mahaney and Kalm 2000; Vos et al. 2014). Origin of mechanically upturned plates on the quartz grain surfaces is due to the influence of high-energy collision during fluvial transport (Vos et al. 2014), which varies from common to sparse in the studied quartz grains. V-shaped percussion cracks, different types of pits, and etched surface microtextures are omnipresent in the studied quartz grains (Figs. 2, 3, and 4). The above features indicate that they were developed by impact among grains through transportation in the fluvial systems.

### Impact of aeolian environment on quartz grains

Surface microtextures of quartz grains resulting from grain-to-grain collisions in aeolian environment show diversity of roughness (Vos et al. 2014; Szerakowska et al. 2018). Mechanically upturned plates developed in high-energy grain-to-grain collisions are common in the Kuakata beach points (Fig. 2), indicating that they are produced by high-impact collision or vigorous pressure on the grain surface. Chmielowska and Woronko (2019) also reported that moderately rounded with mat surface develop in convex parts of sand grains are the impact of short residence time abrasion in aeolian environment, while long-run abrasion might generate well-rounded outline and entirely cover mat surface. However, roundness of sand grains in aeolian environments are likely controlled by the influx of recycled sediments transported from fluvial environments or of saltation process (Vos et al. 2014; Szerakowska et al. 2018). Recycled sediments are common in the investigated beach sands (Hossain et al. 2018), reflecting that they were derived from diverse sedimentary environments. Flat cleavage surfaces and crescentic gouges on quartz grain surfaces are usually formed by impact or pressure on grains in both aeolian and glacial environments (Krinsley and Doornkamp 1973; Vos et al. 2014). These surface features are abundant in the studied quartz grains (Figs. 2, 3, and 4), which suggest aeolian sediment input to the beach sites.

## Conclusions

We examined microtextures of quartz grains from the Kuakata beach point in Bangladesh to evaluate the transport history, provenance, depositional environment, and paleoclimate conditions. The identified microtextures on quartz grains have been categorized as mechanical (20 features), chemical (five features), and combined mechanical and chemical (five features) origin. The quartz grains exhibited highest frequency of sub-rounded to rounded shape, V-shaped pits, straight or curved grooves, crescent-shaped features, and straight or arcuate steps, whereas lowest frequency for angular to sub-angular quartz grains with straight or curved grooves, straight steps, adhering particles, and pits. The sub-rounded to rounded grains in the Kuakata beach point were subjected to long-distance transport under fluvial settings, subsequently derived from Himalayas. Angular to sub-angular grains with straight or curved grooves in the quartz grains indicate short transport from the neighboring Chittagong-Tripura Folded Belt and/or Indo-Burman Ranges. Some samples exhibited high percentages of different pits and adhering particles. Rounded to well-rounded quartz grains have low relief with dish-shaped depressions, mechanically upturned plates, and arcuate and circular surface features suggesting that these grains were subjected to shoreface environments and/or aeolian process. Chemical etched surface, solution/irregular pits, and differential relief were also common in the studied quartz grains representing subaqueous collision during sediment transport in fluvial or nearshore environment. In addition, several quartz grains with smooth surfaces also contain adhering particles indicating subaqueous environment or direct indication of glacial grinding. Dull appearance on quartz grain with polished surfaces, silica precipitation and abrasion, and small V-shaped pits were observed in the quartz grains, which suggests fluvial environment. The chemical precipitation features such as silica globules and silica flowers are indicating humid climatic conditions associated with subaqueous environment.

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