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Research Article

Mineralogical Characteristics and Surface Texture of Quartz Grains in Coastal Sabkha Deposits on the Southern Red Sea Coast

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Abstract

Surface sediment samples from Yakhtul sabkha, located within a local depression east of the Red Sea in Yemen, were analyzed by X-ray diffraction analysis and scanning electron microscopy to determine the mineralogical composition and microtextures of quartz grain surfaces of recent coastal sabkha sediments. Eleven surface sediment samples were collected from the sabkha for this study. The results revealed that X-ray diffraction analysis identified the mineral components in the sabkha sediments, including evaporate minerals such as gypsum, anhydrite, and halite. These minerals indicate the arid conditions prevalent in this coastal environment. Carbonate minerals such as calcite, aragonite, and dolomite were also identified. Conversely, non-evaporite minerals were also identified, including quartz, plagioclase, and orthoclase. The microtextural features of the quartz grains were characterized by a dominance of surface-chemical features generally developed by precipitation and dissolution of recent silica in the near-surface diagenetic environment. In Addition, surface features such as upturned plates, V-shaped pits, elongated depressions, conchoidal fractures, and straight-curved grooves indicate prevailing mechanical processes. Analyzing the surface features of quartz grains using a scanning electron microscope provides significant interpretations of the environmental conditions the grains encountered, allowing inferences about the sediment source.

Keyword: Yakhtul sabkha; Mineralogy; SEM; Red Sea Coast; Yemen

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1. Introduction

Sabkha, or coastal salt flats, are common geomorphological features in arid and semi-arid regions. They are formed by evapotranspiration and sedimentation in environments where freshwater conditions support the development of endoreic drainage systems (Goudie and Wells, 1995; Thomas, 2011). These flat, barren surfaces are characterized by a dynamic equilibrium, influenced by eolian deflation and sedimentation that are regulated by the local water table level (Basyoni and Aref, 2016). The environmental fluctuations of sabkhas, influenced by climatic factors, hydrological conditions, and geological processes, are crucial in forming unique sedimentary structures through displacive, replacive, and inclusive growth processes (Handford, 1982). Furthermore, they support diverse microbial sedimentary features, including pinnacles, pustular forms, gas domes, and sediment volcanoes (Aref and Taj, 2013, 2017; Aref et al., 2014; Cuadrado et al., 2014; Mollai et al. 2014; Warren, 2016; Arjmandzadeh et al. 2020; Ashrafi et al. 2024). They promote the formation of evaporite minerals, which vary in lateral and vertical distribution across the sabkha (Aref and Taj, 2018). Evaporite sediments, or evaporites, are formed by the chemical precipitation of minerals from saline solutions that reach high concentrations due to intense evaporation of water. These deposits typically develop at the margins of ponds and lakes in coastal saline environments (Sabkha) characterized by arid and elevated temperatures. Evaporite minerals in sabkha precipitate from solution in reverse order of their solubility, starting with less soluble minerals such as carbonates, then sulfates, and ending with more soluble minerals such as chlorides. The sequence of precipitation from seawater occurs as follows: calcite, dolomite, gypsum, anhydrite, halite (sodium chloride), and subsequently various potassium and magnesium salts (Haldar and Tišljar, 2014).

Additional components of the sabkha deposits comprise siliciclastic materials, primarily sourced from the neighboring highlands. These materials mainly consist of sand aeolian and gravel formed of quartz, plagioclase, and orthoclase, transported by wind and intermittent runoff (Al-Aydrus et al., 2023). During their transport, various surface features (microtextures) develop due to mechanical and chemical erosion in subaqueous and aeolian environments. In the sabkha, quartz grains predominantly exhibit chemical surface features, including those from silica dissolution and precipitation, such as solution pits, silica globules, trapped diatoms, and adhering particles. Mechanical features, including V-shaped marks and straight and curved scratches, arise from a combination of fluvial processes and high-energy subaqueous beach conditions. In contrast, aeolian grains are primarily characterized by crescentic percussion marks, elongated depressions, and upturned plates (Al-Aydrus et al., 2023; Ait Haddou et al., 2025). Microscopic analysis of the surface microtexture of quartz sand grains has become a significant technique for reconstructing sedimentary environments (Fang et al., 1987; Mahaney, 1998; Udayaganesan et al., 2011; Wasel, 2012; Vos et al., 2014; Mahaney et al., 2014; Chen et al., 2019; Jehangir Khan et al. 2021; Wang et al., 2024). Studies have shown that the microtextures of quartz grain surfaces, revealed by scanning electron microscopy, are powerful tools for interpreting the depositional environments, identification of provenance, transport mechanisms, and diagenetic processes associated with coastal, fluvial, and glacial deposits. These studies have confirmed that the surface features of quartz grains, resulting from mechanical and chemical processes, are distinctive and have been classified and described according to their depositional environments (Al-Saleh and Khalaf, 1982; Krinsley and Doornkamp, 2011; Wasel, 2012).

Coastal sabkhas are widespread throughout the arid eastern coast of the Red Sea, from Bab el-Mandeb in the south to the Gulf of Aqaba in the north, between subtidal to high intertidal zones (Alanazi and Ghrefat, 2013). In some places, evaporative sediments are deposited due to the strong influence of seawater. Other common features of these marshes are high salinity and dryness. They are essential to regional ecosystems because they support a diverse range of halophytic (salt-tolerant) plants and provide habitat for various animals. Numerous sabkhas have been extensively studied, especially those along the Saudi coastline (El Abd and Awad, 1991; Basyoni and Aref, 2016; Aref and Taj, 2018; Aref and Mannaa, 2021). In contrast, limited studies have been conducted on coastal sabkhas on the Yemeni side of the Red Sea; thus, there is a considerable gap in information about their mineral composition and sedimentary properties (Wasel, 2008, 2012; Al-Aydrus et al., 2023; Wasel and Albadran, 2024). Therefore, this paper aims to determine the provenance and depositional environment of sediments by analysis the mineral characteristics and microtextures of quartz grains present in sabkha deposits.

2. Study Area

Yakhtul sabkha is located on the eastern coast of the Red Sea, 160 km south of Hodeidah city, Yemen, between latitudes 13 25 05.54 - 13 25 05.85 N and longitudes 43 15 26.79 – 43 15 19.24 E (Fig. 1) Its length is 9.5 km, and its maximum width in the middle reaches 2 km. The sabkha surface slopes east to west towards the coast, separated by a broad beach ridge. Additionally, the sabkha is separated from the sea by coastal dunes, as shown in (Fig. 1) (Wasel and Albadran, 2024). The sabkha is situated within the vast Tihama Plain, which extends roughly 1,100 km from the northern part of Saudi Arabia, near the Gulf of Aqaba, to the southern region of the Red Sea and the Gulf of Aden. Its maximum width in the southern section reaches 60 km. The Yemeni coastal plain of Tihama extends along the Red Sea coast to Midi in the north. It is about 500 km long and 30-60 km wide and occupies approximately 10% of the total area of Yemen (Geukens, 1966; El-Anbaawy, 1985; Kumar et al., 2011). The Tihama Plain is characterized by its width in the southern part, which gradually decreases towards the north. It is bordered to the east by the mountainous Red Sea highlands and is characterized by a composition consisting mainly of basic and acidic volcanic rocks, in addition to granite rocks dating mostly to the Tertiary period. The mountain slopes in the eastern part of the Tihama Plain are distinguished by the presence of numerous well-formed drainage channels, commonly referred to as wadis. Rainwater flows through these wadis intermittently during the year westward towards the Red Sea, and sometimes, these wadis disappear in the Tihama coastal plain, such as Wadi Rasyan. The sabkha receives large amounts of clastic sediments from the surrounding eastern Red Sea highlands, especially during the rainy seasons across the wadis. Therefore, this sabkha is predominantly covered by Pleistocene and recent deposits with a muddy sand texture, especially in low-lying areas, valleys and tidal flats. These deposits consist mainly of 1% gravel, 86% sand, and 13% mud (El-younsy et al., 2017; Wasel and Albadran, 2024).

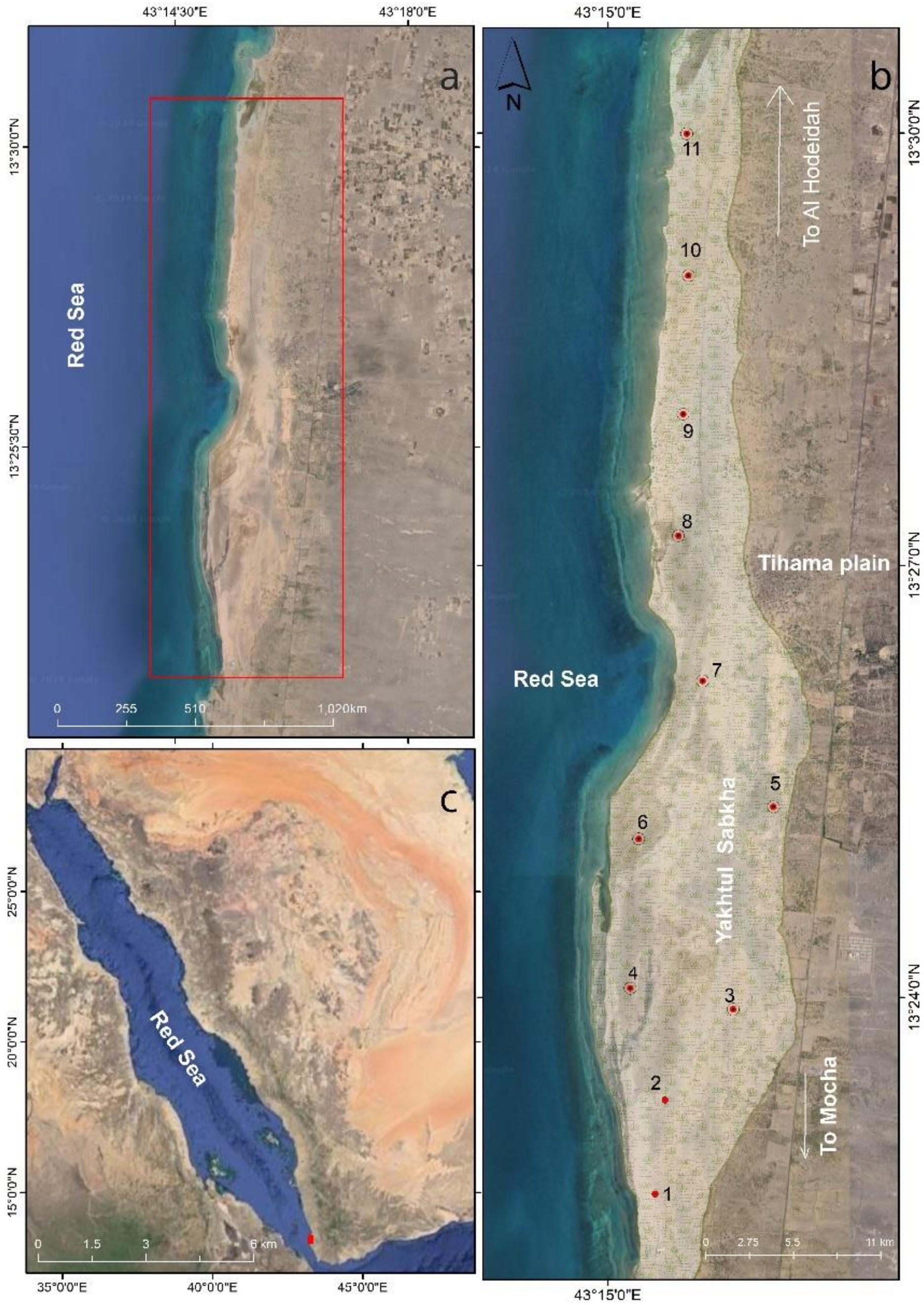

Figure 1. a Map of the location of Yakhtul sabkha showing the geomorphological features of the study area on the Red Sea coast, **b** Distribution of samples in the sabkha area, **c** Location of the sabkha on the Red Sea

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Extensive parts of the sabkha are covered with isolated patches of vegetation characterized by their ability to tolerate hyper-salinity. Furthermore, coastal features, including mangroves, dunes, spits, and lagoons, are found throughout the coastal region. The elevation of this sabkha typically ranges from 3 to 30 meters above sea level. While there is no direct surface connection to the open sea, the sabkha receives seawater through subsurface seepage and filtration, which is influenced by the ebb and flow of tides in the open sea (Fig. 1) The coastal Yakhtul sabkha occurs under a hot and dry tropical climate and has relatively low rainfall, typically between 100 and 200 mm per year. The sabkha is fed with fresh water by intermittent streams, occasionally coming from the eastern highlands during the rainy seasons or seawater through subsurface seepage (Wasel and Albadran, 2024).

The humidity level in the area is about 60 percent. The prevailing winds are generally north-northwest (NNW) and south-southeast (SSE) and vary according to seasonal changes that characterize the southern Red Sea (Guagliardi et al 2016). The surface water salinity in the Yakhtul sabkha ranges between 37.3 to 38.73 ‰, while the temperature varies between 32.10 and 34.40°C (Rushdi et al., 1994). The climatic conditions of the sabkha are similar to those present in other sabkhas along the Red Sea coastal regions (Al-Dubai et al., 2017a).

3. Material and Methods

Eleven surface sediment samples were recovered from the sabkha. A small portion of each sample was thoroughly washed with deionized distilled water to eliminate all salts and then dried in an oven at about 60 °C.

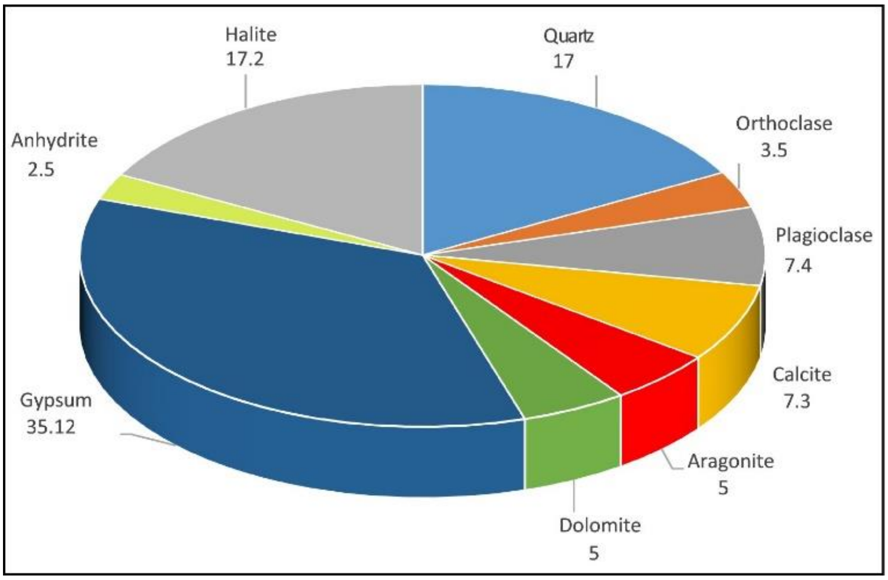

Figure 2. Relative percentages of bulk minerals in the Yakhtul sabkha sediments, determined by X-ray diffraction

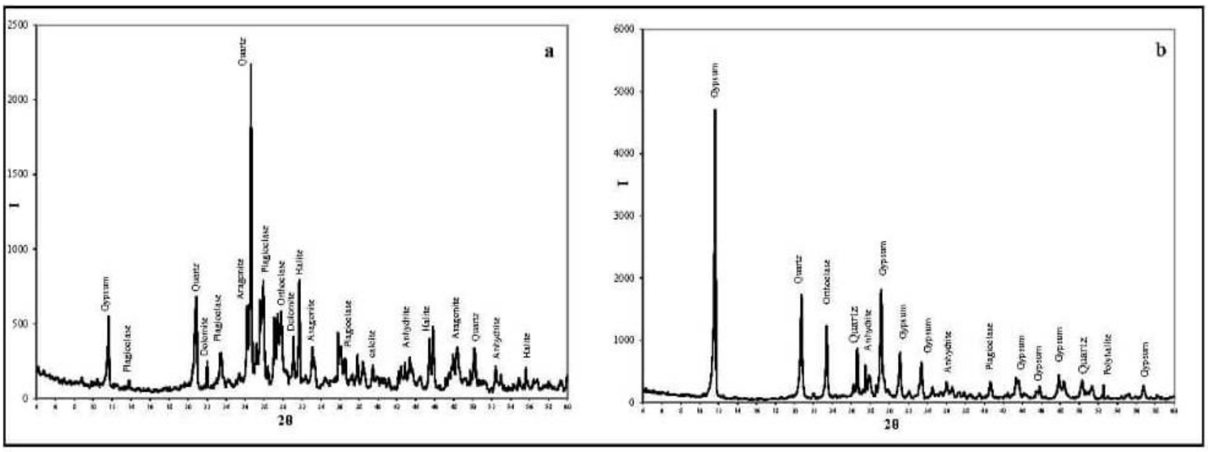

Figure 3. X-ray diffractograms illustrating the bulk mineralogy of the studied sabkha sediments (sample a and b)

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After drying, the samples were ground using an agate mortar and passed through a 0.063 mm sieve. The bulk mineral content of each sample was analyzed by X-ray diffraction (XRD) using a Philips X-ray diffractometer at Assiut University, Egypt, equipped with a Cu Kα radiation tube and a Ni filter and operated at 30–45 kV and 35 mA. The powdered samples were placed in aluminum holders and scanned from 4° to 40° 2θ at a rate of 1.2° 2θ/min. Mineral identification was performed by detecting the characteristic diffraction peaks, utilizing the key line tables provided by Chen (1977). The peak height of the maximum intensity for each mineral was measured, and the relative percentages of each mineral were determined using the methods described by Tucker (1988).

The medium-grained sand fraction was specially chosen from the studied samples to analyze the surface texture. Before the scanning electron microscope (SEM) examination, the cleaning procedures for quartz sand grains were carried out following the methods detailed by (Krinsley and Doornkamp, 2011). Diagnostic features of sand grain surfaces were identified and photographed using a scanning electron microscope (model JEOL-JSM-5400LV) at Assiut University of Egypt.

4. Results and Discussion

4.1. Bulk Mineralogy

Based on the mineralogical analysis of the coastal sabkha samples using X-ray diffraction (XRD), the sediments were found to consist of two main types of components: evaporite minerals, including gypsum, halite, calcite, dolomite, aragonite, and anhydrite, listed in order of their abundance in the sample. The second component consists of non-carbonate terrigenous inputs, such as quartz, plagioclase, and orthoclase (see Figs 2, 3, 4) Gypsum is the most abundant evaporite mineral belonging to the sulphate mineral, and its content in the surface sediments of sabkha Yakhtul ranges from 24.8% to 48.6%, with an average of 35.1%. Halite is the second evaporite mineral recorded in the investigated area, with percentages varying from 11.3% to 24.3% and an average of 17.2%. Finally, the anhydrite content varies between 0.0% and 7.8%, with an average of 2.5% (Fig. 4) These components consist of sulfate and chloride deposits that precipitate after carbonates in natural environments since carbonates typically form at higher temperatures and lower salinities than sulfates and chloride deposits.

The carbonate minerals are primarily calcite, with smaller amounts of aragonite and dolomite. Calcite concentrations range from 1.5% to 14.3%, averaging 7.3%. Aragonite is only present in the trench samples, with values between 0% and 14.1%, and an average of 5.0%. The aragonite occurrence is most probably related to the existence of shells and bioclasts derived from coastal area. Dolomite values vary from 0% to 15.2%, averaging 5.0%. The sabkha under study shows a low percentage of carbonate minerals, similar to the El Belayim sabkha deposits along the Gulf of Suez (Gavish, 1974), reflecting the almost similar chemical and physical conditions of the sabkha environment. Moreover, it indicates a lower rate of marine sediment formation and, thus, slower development and expansion of sabkha, in contrast to the sabkha of the Persian Gulf (Gavish, 1974). The low content of aragonite can be attributed to the fact that the aragonite is being replaced with calcite in the marine environment due to its relative instability (Kinsman, 1969). Low percentages of dolomite may indicate insufficient brine to cause significant dolomitization or that the sabkha is still relatively young. Several studies have reported that although dolomite is common in the geological record, it is rare in modern shallow marine environments (Suzuki et al., 2006; McKenzie and Vasconcelos, 2009). Dolomite occurs in consistently low concentrations, making it difficult to speculate whether its origins are allochthonous or autochthonous; however, the geochemical results may suggest the occurrence of dolomitization (Gavish, 1974). According to a recent study, microbial activity is usually responsible for the precipitation of Mg-carbonate minerals, such as Mg-calcite and Ca-rich dolomite, which frequently occur in salty environments in conjunction with other evaporitic minerals (Sánchez-Román et al., 2023). The precipitation of magnesium-rich carbonates is facilitated by the ability of microbial cells to modify the physical and chemical parameters of their environment, including pH, carbon dioxide concentrations, and metal ion levels (Braissant et al., 2007; Sánchez-Román et al., 2011).

The localized occurrence of calcite near the water table is likely related to its evaporitic precipitation origin. The association of calcite with dolomite and/or aragonite is most probably linked with the diagenetic alteration of the carbonate minerals of the bioclasts and shells. The formation of evaporite minerals and their distribution is controlled by the composition and the direction of the groundwater (Kendall, 2005). Therefore, the groundwater, which formed the evaporite minerals, flowed upwards. This also indicates that calcite and gypsum were deposited earlier than halite due to the differences in their solubility products.

Another source of carbonate minerals (calcite, aragonite, and dolomite) is detrital inputs, which include ancient unconsolidated limestone deposits transported from the limestone highlands near the coastal area or sediments derived from the limestone reef terraces in the coastal regions. Moreover, the carbonate deposits in the sabkha include small quantities of biogenic sand enriched with calcareous algae, coral debris, mollusc shells, and foraminiferal tests, which are carried from offshore areas to the sabkha by wave action and tidal currents (Bantan and Abu-Zied, 2014; Al-Dubai et al., 2017b, 2022; Bantan et al., 2019; Ghandour et al., 2021).

In general, evaporite minerals are formed in coastal sabkhas, whether they are open sabkhas or those isolated from seawater by sand berms along the coast. The difference between them, however, is that the first type of coastal sabkhas receive its seawater supply through periodic flooding events and tidal inundation. The second type of sabkhas relies only on seawater intrusion through capillary action as the exclusive source of its seawater supply, without any direct surface water inputs. In other words, sabkha recharge through seawater intrusion alone is insufficient to form the large quantities of evaporative deposits necessary for the growth, development, and expansion of sabkhas. In contrast, coastal sabkhas that receive direct input from seawater, such as those of the Trucial Coast sabkhas, tend to develop more rapidly compared to sabkhas that rely only on seawater intrusion (Kinsman, 1969). In the case of the Yakhtul Sabkha, the sediments are primarily dominated by evaporite formations, which closely resemble the Trucial Coast sabkha on the Persian Gulf (Kinsman, 1969); however, the Yakhtul Sabkha did not develop as extensively as the sabkhas found in the Persian Gulf region, perhaps because seawater seepage into the sabkha was limited, or its development began at a later time. On the other hand, the sedimentation process in the Yakhtul Sabkha is analogous to what occurs in several sabkhas found along the Red Sea (Gavish, 1974; Aref and Taj, 2018) and the Gulf of Suez coasts (Gavish, 1974).

In Yakhtul sabkha, gypsum is the predominant evaporite mineral. It is deposited in both subaqueous environments, including shallow and deep waters, and in the subaerial zones of the coastal sabkha (Aref et al., 1997; Wilson et al., 2013). Kinsman (1969) reported that gypsum deposits typically occur in horizons 20-40 cm below the surface, and can also be seen within upper intertidal zone sediments. Gypsum deposits typically occur in areas with arid, dry, and hot climates, significantly when evaporation rates exceed the water flow rate, leading to an increased concentration of salts in the water to about 3.5 times the salinity of seawater i.e. about 120% (Haldar, 2020). At this concentration, gypsum begins to crystallize at 30 °C and continues to form until the salt concentration in the water reaches 4.8 times that of normal seawater. The persistent dehydration and intense evaporation of sabkha water, particularly at temperatures between 25°C and 35°C in an arid climate, result in a substantial increase in calcium sulfate concentrations and salinity, reaching levels approximately 4 to 7 times higher than the normal salinity of seawater (Haldar, 2020). Ultimately, it leads to the formation of anhydrite deposits in the sabkha. In addition, anhydrite can also arise from the dehydration of gypsum deposits that originated in the intertidal zones (Haldar, 2020; Aref and Mannaa, 2021). Haldar (2020) noted that sabkha anhydrite is produced in significant quantities alongside early diagenetic dolomite in coastal saline environments or sabkhas.

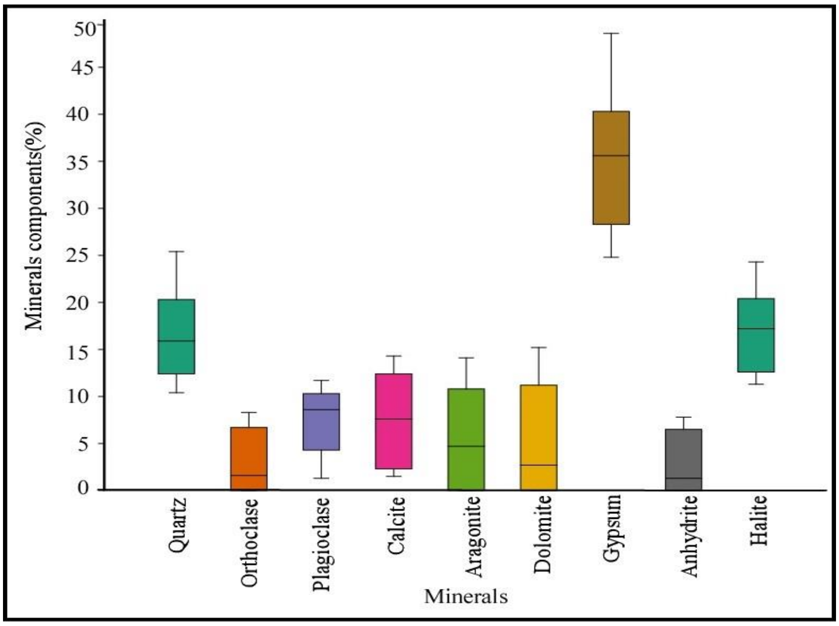

Figure 4. shows the proportions of mineral components in samples collected from the Yakhtul sabkha

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Anhydrite is one of the primary evaporite minerals found in the sabkhas of the Persian Gulf (Kinsman, 1969). In contrast, the Yakhtul in the southern Red Sea and El Belayim sabkhas along the Gulf of Suez described by (Gavish, 1974) are dominated by the evaporite mineral gypsum, however, anhydrite in the latter sabkhas constitutes only a low proportion of the minerals present. This suggests that the sabkhas in the Persian Gulf exist under more arid conditions than those in the Red Sea and the Gulf of Suez.

Clastic minerals are represented by quartz and feldspars. Quartz occurs in all samples in amounts ranging between 10.4% and 25.4%, with average of 17.0%. Feldspar minerals are mainly represented by plagioclase and orthoclase (k-feldspar) Plagioclase was recorded in the investigated sabkha sediments with percentages ranging from 1.3% to 11.7%, with an average of 7.4%, while orthoclase fluctuated between 0.0% and 8.3%, with an average of 3.5%. The presence of these clastic minerals suggests the partially siliciclastic nature of the studied sabkha. In general, a marked concentration in the clastic constituents controlled significant differences in the mineralogy. These minerals (quartz, plagioclase, and orthoclase) are derived from the eastern Red Sea mountains, which are composed of Tertiary volcanic rocks (El-younsy et al., 2017) and transported either by eolian or through intermittent wadis that are active during rainy seasons and flow into the coastal plain. The dominance of plagioclase feldspar over the k-feldspar can be attributed to the igneous origin (Wasel, 2008; El-younsy et al., 2017).

Microtextures on quartz grains surface

Numerous researchers have shown that microtextures on quartz grain surfaces can be employed to identify various sedimentary environments, transport mechanisms, and their association with source rocks and origins

(Krinsley and Doornkamp 1973; Mahaney 2002; Armstrong-altrin and Natalhy-pineda 2014). Thus, the examination of surface textures on quartz grains is regarded as an effective tool for identifying provenance, transport processes, and the diagenetic history of clastic sediments (Krinsley and Doornkamp, 1973, 2011; Mahaney et al., 2004; Kleesment, 2009; Udayaganesan et al., 2011; Wasel, 2012; Hossain et al., 2014, 2020; Ramos-vázquez and Armstrong-Altrin, 2021; Al Buloshi, Gheith, 2022; Armstrong et al., 2022).

Different mechanical and chemical processes create distinct markings on the surfaces of quartz grains, enabling the identification of specific depositional environments. For instance, quartz grains may display mechanical features like V-shaped marks, impact scars, conchoidal fractures, and straight-curved grooves, all of which suggest a fluvial environment. Chemical characteristics, including silica globules, solution pits, adhering particles, and crystal overgrowths on quartz grains, suggest a diagenetic environment and silica re-precipitation in a coastal setting. The occurrence of mechanical features (bulbous edges) and chemical features (silica overgrowths, solution pits) within a single grain implies a dual depositional environment, reflecting both littoral and subaqueous coastal settings (Krinsley et al., 1976; Abu-zeid et al., 2001; Kalińska-Nartiša et al., 2017; Madhavaraju et al., 2022).

Al-Saleh and Khalaf, (1982) noted that chemical features are predominant in the sabkha deposits. Conversely, Wasel, (2012) indicated that mechanical features are more common in wadi deposits, coastal dune sands, and beach sands, with grooves being the most frequently observed feature, followed by impact V-marks and conchoidal fractures. The rounding of grains and the smoothing of edges suggest a high-energy environment. Chemical features such as triangular etch pits, silica precipitation, and deep grooves are prevalent in the sabkha deposits. Furthermore, the presence of diatoms on the quartz grains from the beach indicates the occurrence of chemical precipitation in a high-silica environment.

The surface features of quartz grains found in coastal sabkha deposits are illustrated in (Fig. 5) They are characterized by a dominance of chemical features, typically arising solution and precipitation processes, in the recent near-surface diagenetic environment. The chemical features include subrounded quartz grains that are highly subject to chemical action (Fig. 5a), triangular etch pits associated with silica globules (Fig. 5b) Microtextures of chemical origin, such as solution pits and silica globules, likely result from dissolution and precipitation activities during diagenetic processes within the depositional environment, which are typical of intertidal and subaqueous settings. Overall, quartz grains are more susceptible to chemical dissolution in subaqueous marine environments than in arid environments (Hossain et al., 2014; Li et al., 2020).

The surfaces of quartz grains from the sabkha deposits were found to exhibit silica precipitation features, including irregular plates, cavity fillings, and silica plastering (Fig. 5c, d) In this context, excess silica accumulates on the quartz grain surfaces in a non-oriented manner. This phenomenon may be associated with the movement of grains across against one another under high-pressure conditions (Krinsley and Doornkamp, 2011). Silica precipitation was observed on triangular etching pits (Fig. 5e), along with the precipitation and dissolution (etching) of silica on surface grains (Fig. 5f)

The most prominent diagenetic features in this environment are the triangular etch depressions, resulting from extensive chemical etching along planes of weakness. Precipitation and dissolution (etching) are predominantly formed in the recent near-surface diagenetic environment. Increased evaporation rates and the presence of saline brine typically result in a rise in pH, which affects the quartz grains and influences the development of chemical features (Udayaganesan et al., 2011). Furthermore, the dominant mechanical processes observed on some grains, including upturned plates, V-shaped pits, and elongated depressions, are typically attributed to aeolian activity (Higgs, 1979; Mahaney, 2002; Li et al., 2020).

In contrast, fluvial grains exhibit subangular to subrounded shapes with heterogeneous features, including conchoidal fractures and straight-curved grooves (Mahaney, 2002; Kleesment, 2009; Vos et al., 2014),

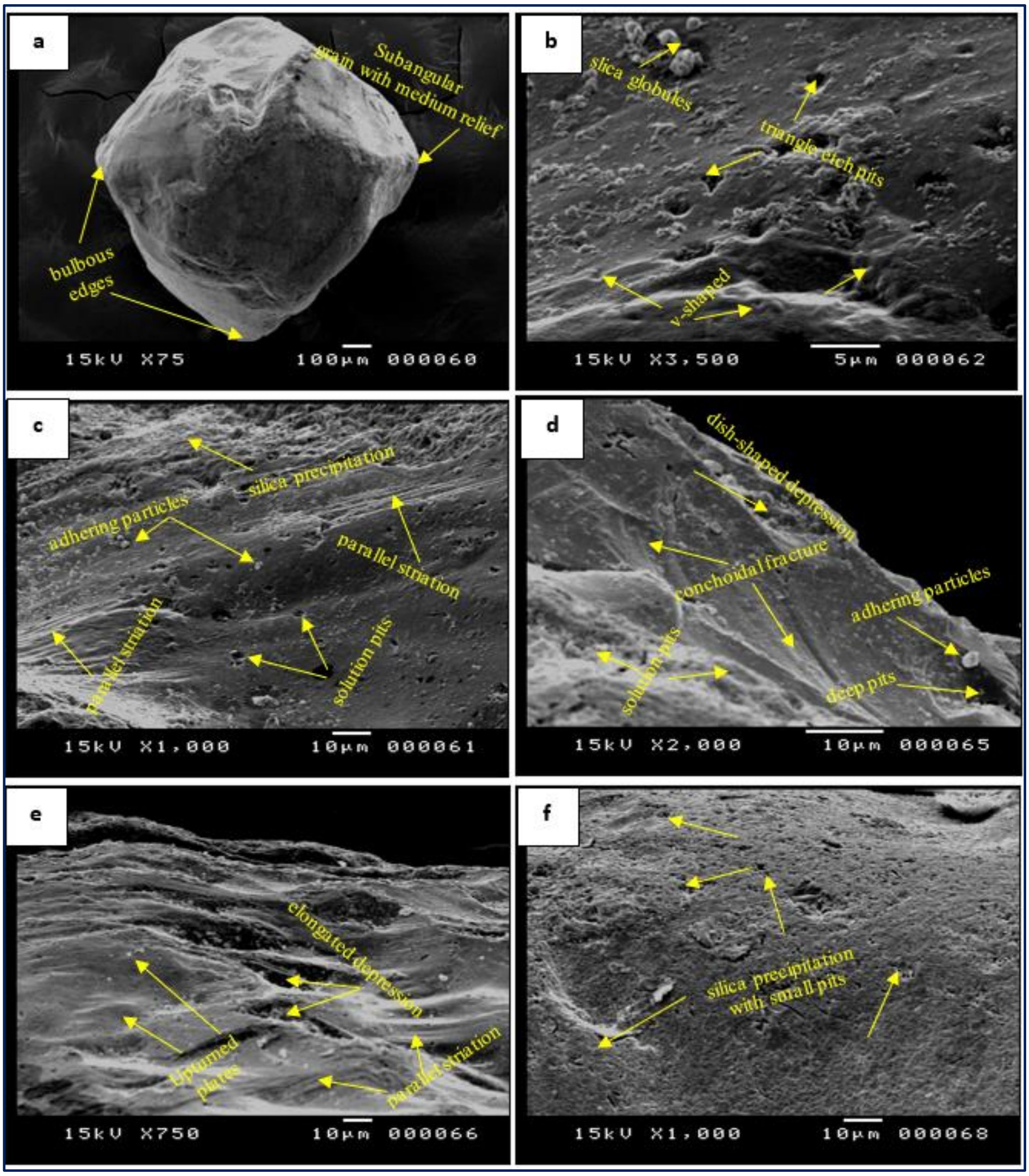

Figure 5. Surface microtextures of quartz sand grains from the sabkha deposit as observed by SEM, **a** Subangular grain with bulbous edges and medium relief, indicative of chemically weathered surfaces, **b** Quartz grain displaying V-shaped patterns and triangular etch pits associated with silica globules, **c** Quartz grain featuring irregular small pits, parallel striations with adhering particles, and silica precipitation on the surface, **d** Quartz grain exhibiting dish-shaped depressions linked to conchoidal fractures, adhering particles, and deep pits modified by silica dissolution, **e** Steps with parallel striations, upturned plates, and elongated depressions partially filled with silica, **f** Silica precipitation on the grain surface accompanied by small pits

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which remain well preserved despite the impacts of subsequent diagenetic processes, including those resulting from the dissolution and precipitation of silica on grain surfaces.

5. Conclusions

Sabkha Yakhtul is a coastal sabkha in the southern part of the Red Sea and occurs under arid climatic conditions. Mineralogical analysis and scanning electron microscopy of the sabkha sediments have revealed the presence of several evaporated minerals, including gypsum, halite, and anhydrite. Additionally, the sediments contain carbonate minerals such as calcite, aragonite, and dolomite, as well as detrital deposits of quartz and plagioclase. The halite deposits appear in the salt crusts, predominantly in the upper areas of the sabkha, reflecting the well-developed nature of the sabkha. The formation of sabkha deposits is due to the evaporation of seawater, its mixing with occasional rainwater, and the seepage of groundwater as a continental flow. Sabkha quartz grains are characterized by a predominance of surface chemical features that generally develop by precipitation and solution of modern silica in the near-surface diagenetic environment. In addition, the prevailing mechanical processes reflect the fingerprints of the original aeolian and fluvial environment of some grains, despite the influence of diagenesis.

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Authors Contribution
All the authors have participated sufficiently in the intellectual content, conception, and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest
The author states that there is no conflict of interest.

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