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Formation conditions and diagenetic evolution of sand roses in clastic sabkhas along the Arabian Gulf Coastal Region, Eastern Saudi Arabia

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This field, petrographic and geochemical study aims at constraining the formation and diagenetic evolution of sand roses (desert roses) in interdune sabkhas in Eastern Saudi Arabia. These “roses”, which are mainly cemented by gypsum, carbonate, and clay minerals, occur as disc-shaped and spherical flower-like crystals. Sands, within the sand roses, are moderately-sorted, medium-grained, and sub-arkosic. Gypsum typically exceeds 20% of the volume of the roses, and locally gypsum is partly transformed to anhydrite. In addition to gypsum and anhydrite, early diagenetic modifications include precipitation of grain coating clay, dissolution of unstable grains (e.g., feldspar grains), and weak mechanical compaction. Iron oxide cement was formed when the sand roses exposed to the surface. The XRD and petrographic data indicate an increase in amounts of gypsum cement from the water table upward towards the sabkha surface. The sand roses also are larger and lighter in colour away from the water table. The formation of sand rose at the water table is attributed to the nonpedogenic process where dynamic interactions between meteoric vadose and phreatic zone occur. This study is expected to provide a better understanding of the mode of sand roses formation in the interdunes areas, as well as the diagenetic alterations in both phreatic and vadose zones.

Key words: sand roses, desert, diagenesis, gypsum, Eastern Saudi Arabia.

INTRODUCTION

Sand rose (desert rose) is a sedimentary rock formed at very shallow depths mostly as a result of the crystallisation of gypsum in terrestrial, lacustrine, and supratidal marine sedimentary environments (Watson, 1985). Gypsum cement is formed when calcium- and sulphate-rich waters are pumped by capillary action to the surface of porous sediments and subsequently evaporate (Warren, 2006); cementation by gypsum creates a unique rosette shape. According to Mougenot (2000), sand roses are originally formed at the water table before exposure to the surface by erosion. Sand roses with the inclusion of sand particles have been found at some localities in the world including North Africa, mainly central Algeria and Tunisia (Watson, 1988; Drake et al., 2004). One of the most well-known examples of sand roses is the large crystal aggregates from the Laguna Madre, Texas (Masson, 1955). Shallow gypsum crusts are documented in the Namib Desert (Watson, 1988; Eckardt and Spiro, 1999; Eckardt et al., 2001), and Australia (Warren, 1982; Chivas et al., 1991; Chen, 1997). Gypsum crusts including sand roses have been found throughout the Middle East, including Egypt (Ali and West, 1983; Aref, 2003), Syria (Eswaran and Zi-Tong, 1991), Jordan (Turner and Makhlouf, 2005), Iraq (Tucker, 1978), and Kuwait (El Sayed, 1993). Saudi Arabia is one of the largest desert countries in the world with prominent arid climatic conditions, which are suitable for the formation of sand roses (Mougenot, 2000; Al Juaidi et al., 2003). These sand roses, which occur in interdune areas (inland sabkhas), are formed from brines saturated with respect to gypsum (Fig. 1). The main goal of this study is to constrain and better understand the formation and diagenetic evolution of sand roses.

GEOLOGICAL BACKGROUND OF THE STUDY AREA

Pleistocene sabkhas containing gypsum-cemented sand roses occur in several areas in the Eastern Province of Saudi Arabia, along the Arabian Gulf (Fig. 2). These sabkhas are covered by modern sand dunes with local outcrops of sandstone and carbonates of the Neogene Hofuf, Dam and Hadrukh formations (Fig. 2). The Hofuf Formation is composed of quartz sandstone at the bottom and conglomerate at the top. The overlying Dam Formation comprises white, reddish brown, and olive coloured mudstones with minor interbedded chalky limestone and coquina-rich grainstones. The Hadrukh Formation comprises mainly of green, greyish-green, or grey coloured sandy

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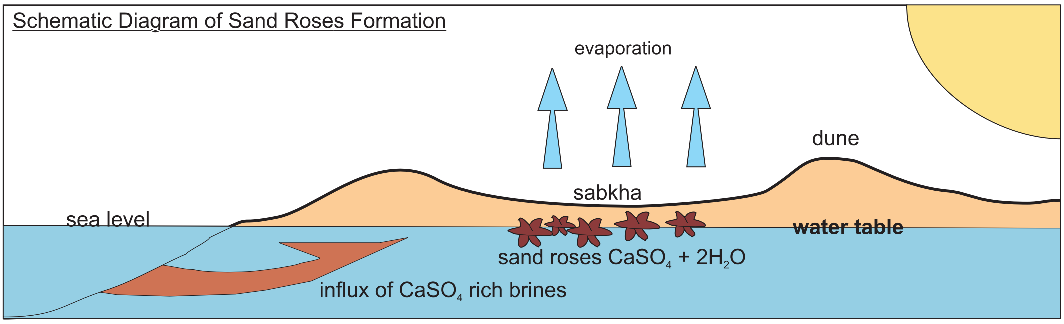

Fig. 1. Illustration of the gypsum roses (sand roses) formation in the sabkha or interdunes area (Mougenot, 2000)

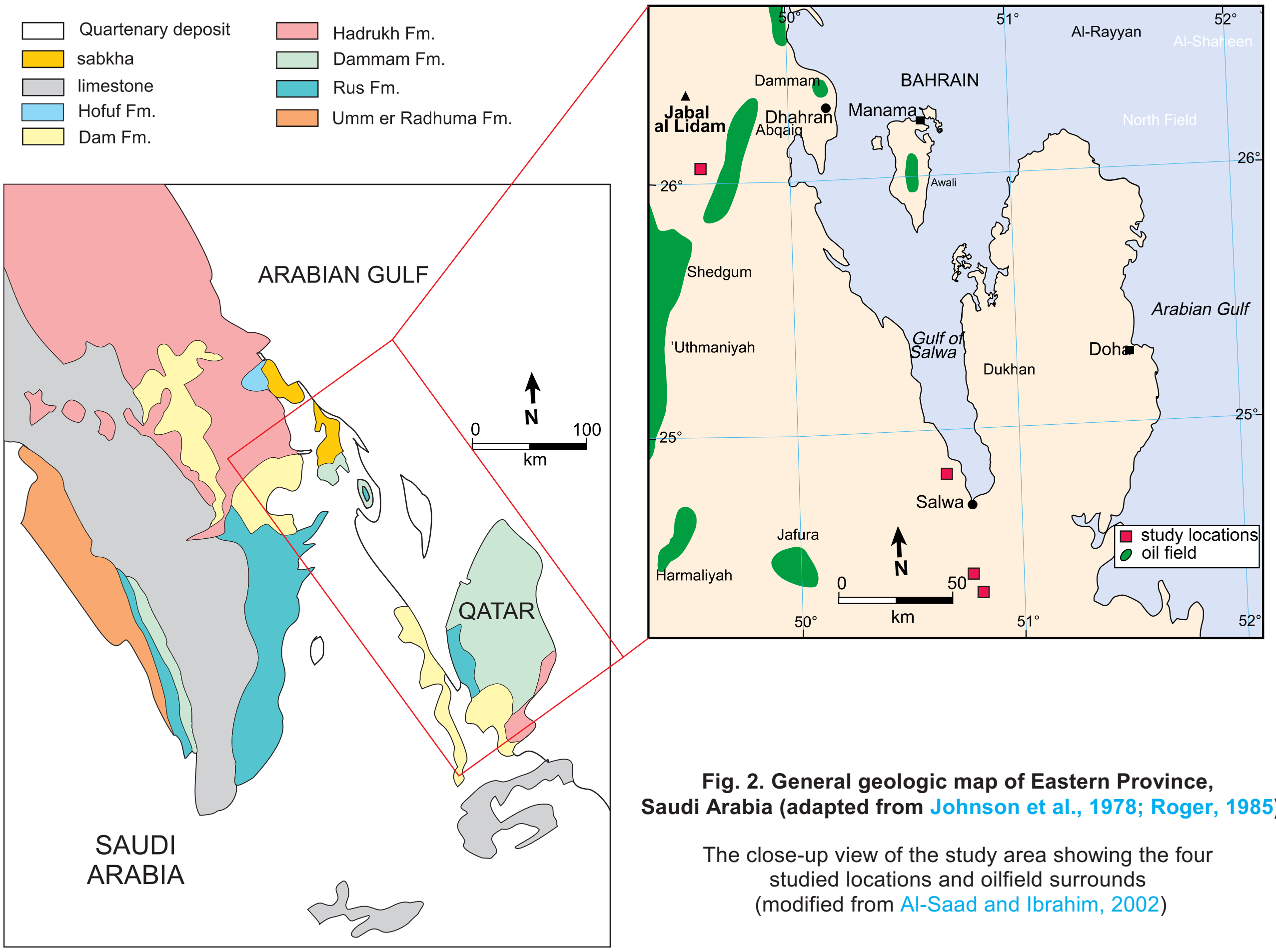

Fig. 2. General geologic map of Eastern Province, Saudi Arabia (adapted from Johnson et al., 1978; Roger, 1985)

The close-up view of the study area showing the four studied locations and oilfield surrounds (modified from Al-Saad and Ibrahim, 2002)

marl, sandy clay, and sandy limestone as most of the unit with minor amounts of gypsum.

Fresh sand roses are typically found within the sabkha sediments between the water table and the surface (about 0.7–1.0 m below the surface). However, weathered sand roses are locally found on the sabkha surface.

SAMPLING AND ANALYTICAL METHODS

A total of twelve fresh and weathered sand rose samples were collected and analysed from two different study areas: Ayn' Dar and Gulf of Salwa, both of which are located in the Eastern Region of Saudi Arabia (Fig. 2). Sand rose samples that were collected at the surface of the interdune sabkhas showed weathering effects (Fig. 3). The fresh samples were collected from about 10 cm to 1 m below the surface of the interdune sabkhas (Fig. 4).

Thin sections were prepared for a total of eight representative samples selected from different interdunes areas and subjected to modal analyses by 300 points in each thin section. The samples were prepared in the absence of freshwater to prevent excessive dissolution of water-soluble minerals (primarily halite). The thin sections were ground with acetone to prevent the dehydration of hemihydrate (bassanite) and gypsum. Scanning Electron Microscopy (SEM), backscattered electron imaging (BSEI), and powder X-ray diffraction (XRD) were performed for five representative samples in order to determine the chemical and mineral composition of the sand roses.

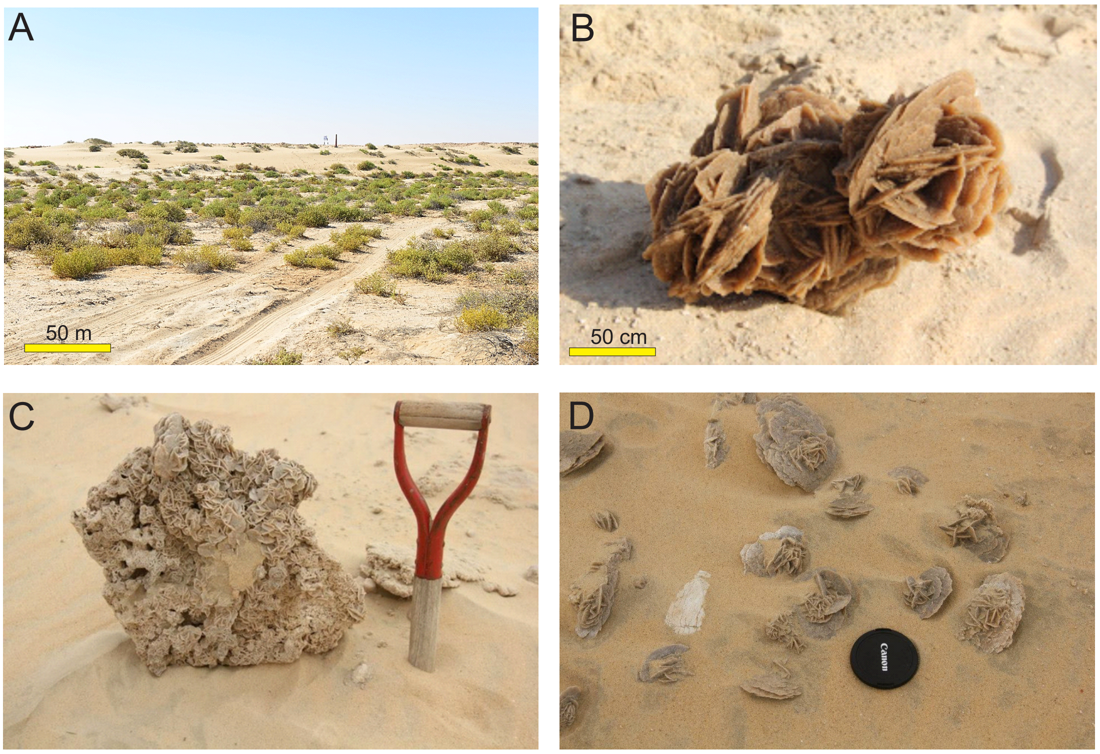

Fig. 3A – interdune area where the first occurrence of sand roses were found; B – sand roses with blades of gypsum crystals with coarse sand grains; C, D – weathered sand roses at the surface of interdune area in Salwa area

Fig. 4. Field photos from Gulf of Salwa

Four different occurrences of sand roses were successfully documented and recognized from one digging hole; samples of sand roses that were found just above the water table

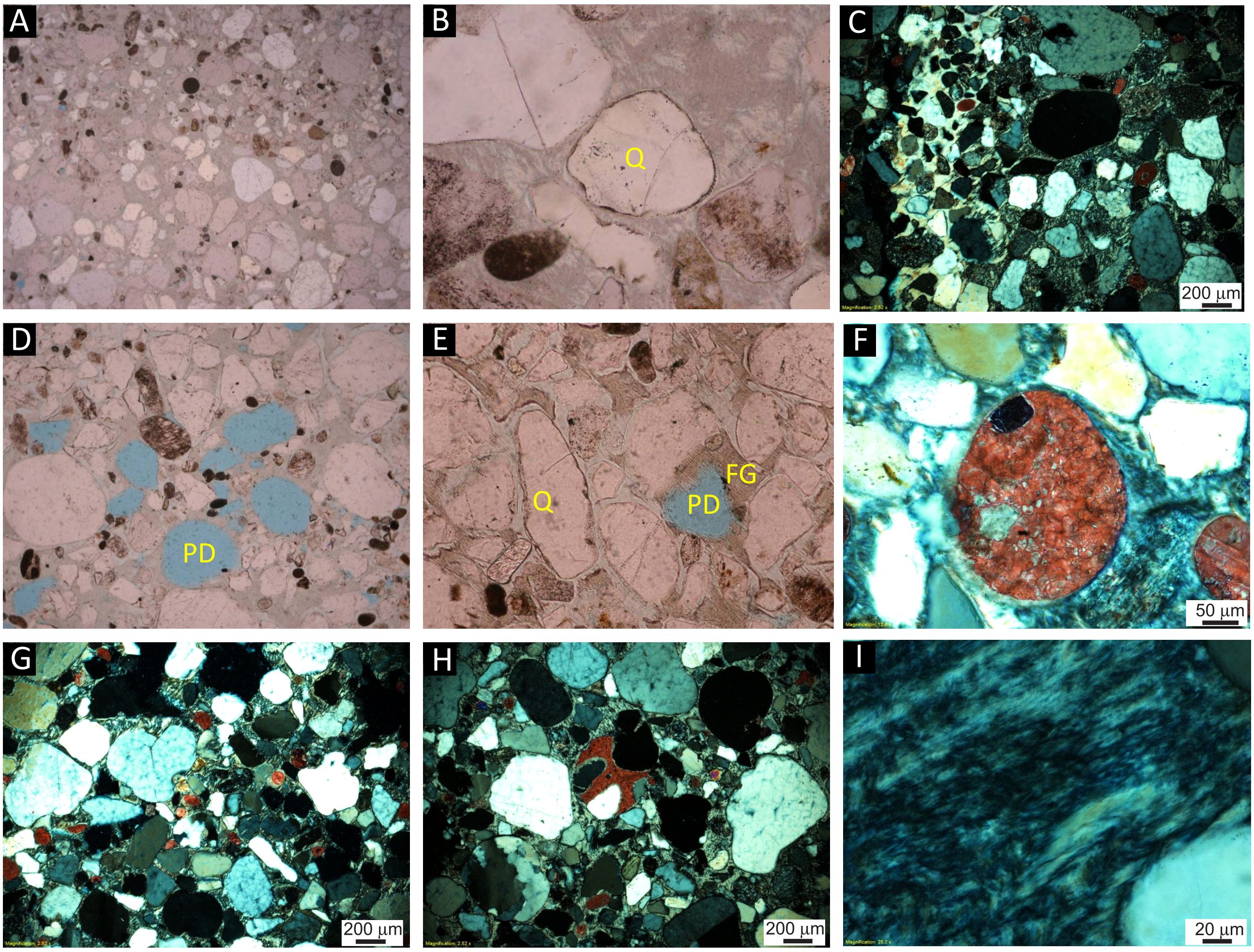

Fig. 5A – bimodal well-sorted quartzose sandstone; laminations are defined by variations in grain size; coarser laminae shows well-rounded grains, whereas finer laminae show sub-rounded grains and an abundance of sedimentary lithics; B – clay coatings on quartz grain (Q) predating gypsum cement; C – fine-grained clasts (i.e., quartz, feldspar) engulfed by poikilotopic gypsum cement; D – well-preserved grain dissolution pores (PD) indicate grain removal post gypsum cementation; E – tangential grain coatings on quartz grains define that quartz overgrowth; fibrous gypsum (FG) cement can be seen etching quartz grain rims, causing localized alteration; F – granitic rock fragments, well-rounded and found scattered within the studied samples; G – extensive mechanical compaction observed from the samples collected near the water table; H – medium to well-sorted sand roses sample mostly comprised of mono- and polycrystalline quartz; I – lenticular gypsum habit

RESULTS

FIELD OBSERVATIONS OF SAND ROSES

In both Ayn' Dar and Gulf of Salwa areas, the subsurface sand roses, which were located at the water table (~1 m), are dark brown in colour and small in size (±10 cm across). Moving away from the water table toward the surface, the sand roses progressively became lighter in colour and larger (~20–50 cm across).

PETROGRAPHIC AND CHEMICAL ANALYSIS OF SAND ROSES

In general, all samples were fine- to medium grained and moderately sorted (Fig. 5). The framework grain compositions of the studied samples were dominated by quartz (av. 70%) feldspar (av. 11%; K-feldspar and plagioclase), and lithic fragments (av. 6.8%). The lithic fragments include carbonate, chert and shale.

The major type of cement in the studied samples is gypsum that constitutes 40–50% on average (Fig. 5). Blocky gypsum is present as intergranular and poikilotopic cement (19.7% average from modal analysis). Poikilotopic gypsum crystals have mainly lenticular habits that vary in dimensions. Other cement phases observed in thin sections and supported by XRD analyses include dolomite (<2.7%), siderite (<1.6%), anhydrite (<0.5%), barite (<0.4%) and haematite (1.6%). Most of the framework grains are floating in the cements but some grains showed point to elongate contacts.

The XRD analysis of sand roses revealed striking evidence that the amount of gypsum in the roses increases toward the sabkha surface, from about 1.1% near the water table (Fig. 6) to about 3.2% near the surface in Ayn' Dar area; and a similar trend in the Gulf of Salwa area, from 12.8% at the first occurrence near the water table to 15.2% towards the interdune surface (Fig. 6B).

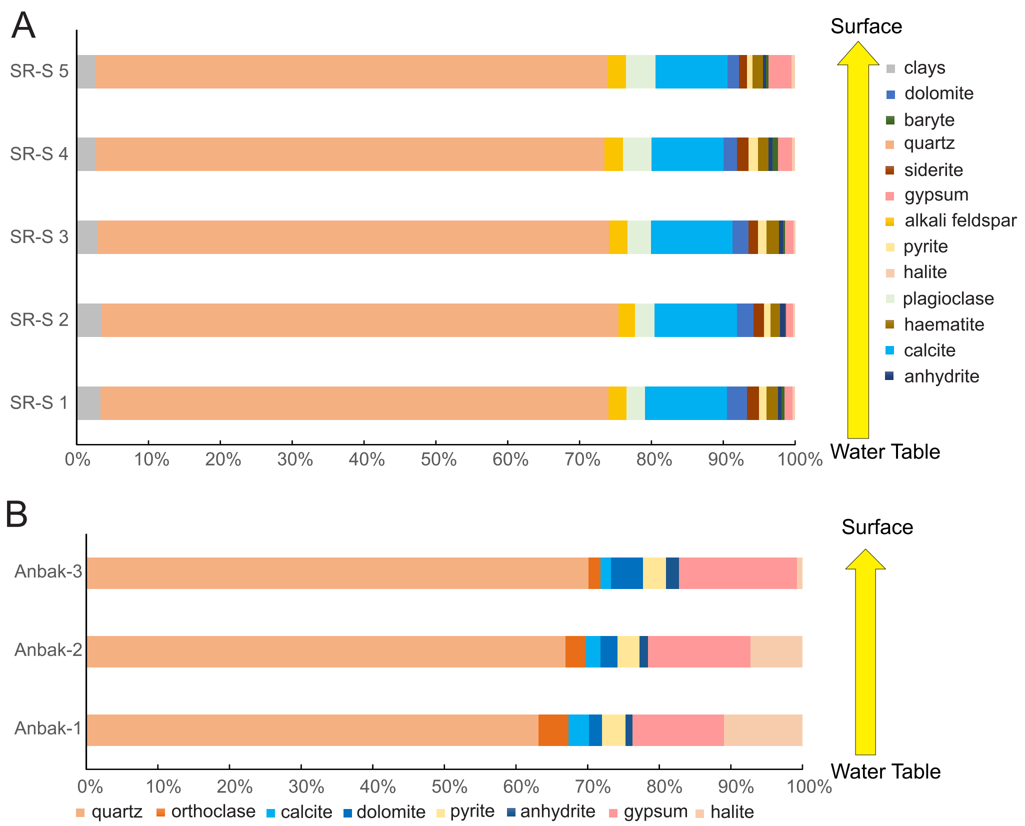

Fig. 6. XRD analysis shows the increase of gypsum concentration towards the surface

In contrast, the concentration of calcite, dolomite and halite are decreasing to the surface; this trends is found in both studied areas

DISCUSSION

MODES OF SAND ROSES FORMATION

The sandy coast of the Eastern Region of Saudi Arabia provides an ideal condition for sand rose formation. The sabkha brines of the Arabian Gulf are concentrated through the evaporation process from the surface of the interdune sabkhas when it seep upward by capillary action into the sand (Mougenot, 2000). The fluctuations of the water table result in continuous precipitation of gypsum crystals in the pore spaces of sands between the water table and the sabkha surface, displacing the loosely-packed sand grains. Cementation by gypsum may explain the transformation of the dark sand and black gypsum crystal to white crystal and light colour sand roses (Fig. 7). These conditions are controlled by the difference in composition of wind-blown sand and gypsum crystal itself and the intensity of evaporation, which becomes more intensive near the surface of the interdune area (Watson, 1985). The increase in the amount of gypsum toward the interdune surface is thus attributed to the progressively increasing rate of evapo-

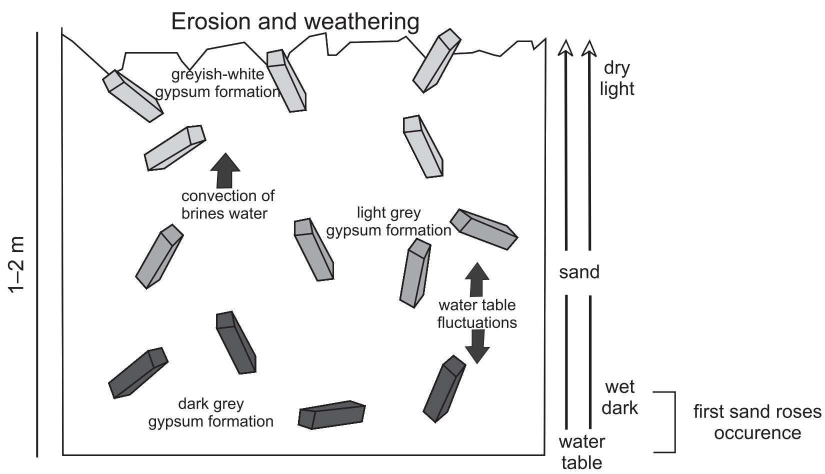

Fig. 7. The schematic model the modes of sand rose formation in this recent study

Dark and small sand roses were found near the water table whereas the lighter and larger sand roses were found in the near surface (adapted from Mougenot, 2000) ration (Fig. 6). One intriguing feature that has been found in any study of sand roses is the appearance of slightly to strongly weathered sand roses on the surface with distinct outsized sand roses (around 60 cm to 1 m across). The most important process in explaining the appearance of weathered sand roses in the interdunes surface is probably exposure caused by wind erosion and deflation of the aeolian sands in association with water table fluctuations.

Results obtained from the present study suggest that sand rose formation can occur via two different mechanisms: pedogenic and nonpedogenic processes. Pedogenic process has been used to explain the development of sand roses by different authors (e.g., Watson 1983; Eckardt et al., 2001). This process describes the accumulation of gypsum as a result of illuviation or capillary rise processes. It requires large amounts of water to generate a thin crust of gypsum, hence must be associated with wetter climate (Reheis, 1987). The second mechanism, which is non-pedogenic process, has been proposed to elucidate the formation of sand rose in the lacustrine environments or near to the groundwater table where dynamic interactions between meteoric vadose and phreatic zone occur. In this model, gypsum in the sand rose crusts in the phreatic zone was probably formed by the evaporation of groundwater where the water table is located around 1 or 2 m beneath the surface. In this study, non-pedogenic model of sand rose formation has been suggested to describe the formation of gypsum close to the groundwater table based on the hydrodynamical and hydrochemical stabilities that allows the formation of coarse-crystalline gypsum (Castens-Seidell and Hardie, 1984). In contrast, the pedogenic mechanism has failed to explain the formation of sand roses in this study due to the lack of clear evidence of illuviation processes and also the arid climatic condition of the study area.

DIAGENESIS AND PARAGENETIC SEQUENCE OF SAND ROSES

A composite, inferred paragenetic sequence for the studied sand rose samples is presented in Figure 8. Early diagenesis started by locally developed, tangential to radially orientated clay (Fig. 9). These grain-coating clays pre-date grain dissolution and gypsum development. Weak mechanical grain compaction is commonly found in the samples by the presence of point to long grain contacts that may indicate near surface burial. The percolating clay rich water into the porous interdune sands may explain the presence of clay coatings around sand grains in the present study. This process is known as illuviation (Fedoroff, 1997; Buurman et al., 1998) and the depth where the clay suspended water can reach is controlled by downward velocity of percolating water, the amount of suspended clay and the sand porosity. As water evaporates, it leaves behind a clay film known as coating (Stoops, 2003). The presence of patches of iron oxide cements is recognized only on the weathered sand rose samples due to subaerial exposure.

Gypsum cement (Fig. 9) is interpreted to be formed under a near surface condition and primary precipitated from oversaturated brine. Gypsum crystals are restricted to environments where annual rainfall is less than 200 mm/yr. and where there is a monthly excess of evaporation over precipitation throughout the year (Watson, 1985). The development of lenticular habit has been attributed to be controlled by the presence of certain organic matter within the host sediments (Cody, 1979; Fig. 6). Anhydrite cement is likely to be a secondary precipitation as a product of transformation and dehydration of primary gypsum. In addition, the occurrence of anhydrite patches cement within gypsum cements in the studied samples may also support the secondary formation of anhydrite. Several authors have argued the possibility of primary anhydrite precipitation in modern evaporites deposit due to the abundance of activating cations in sea water and little preservation chance of primary anhydrite caused by unfavourable elevated humidity conditions (Ritchter, 1961; Warren, 1989).

Hardie (1967) found that dehydration of gypsum to anhydrite depends on temperature (i.e., degree of evaporation) and lowering the activity of water (H_2O).

Some moldic pores resulted from complete dissolution of unstable grains (e.g., feldspar grains) may suggest freshwater diagenesis. During infrequent periods of heavy rainfall, the sabkha surfaces are often flooded, and this freshwater may infiltrate the sands between the sabkha surface and the water table, over time altering the feldspar grains. Most often, the mouldic pores are preserved as secondary porosity.

CONCLUSIONS

The formation of sand roses along the Arabian Gulf Coastal Region is controlled by the fluctuations of the water table, which leads to the precipitation of gypsum crystals in the pore spaces, displacing the loosely-packed sand grains. This study showed an increase in the amount of gypsum toward the interdune sabkha surface due to progressively increasing rate of evapora-

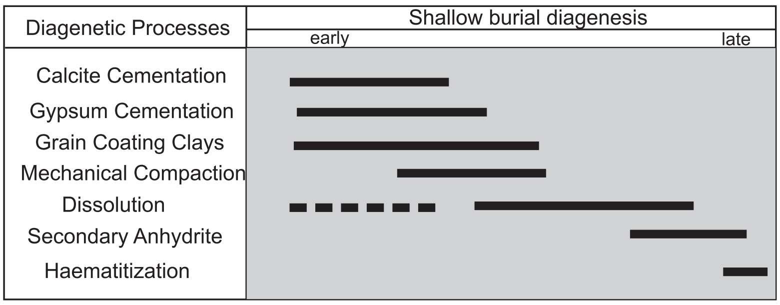

Fig. 8. Paragenetic sequence for studied sand rose samples

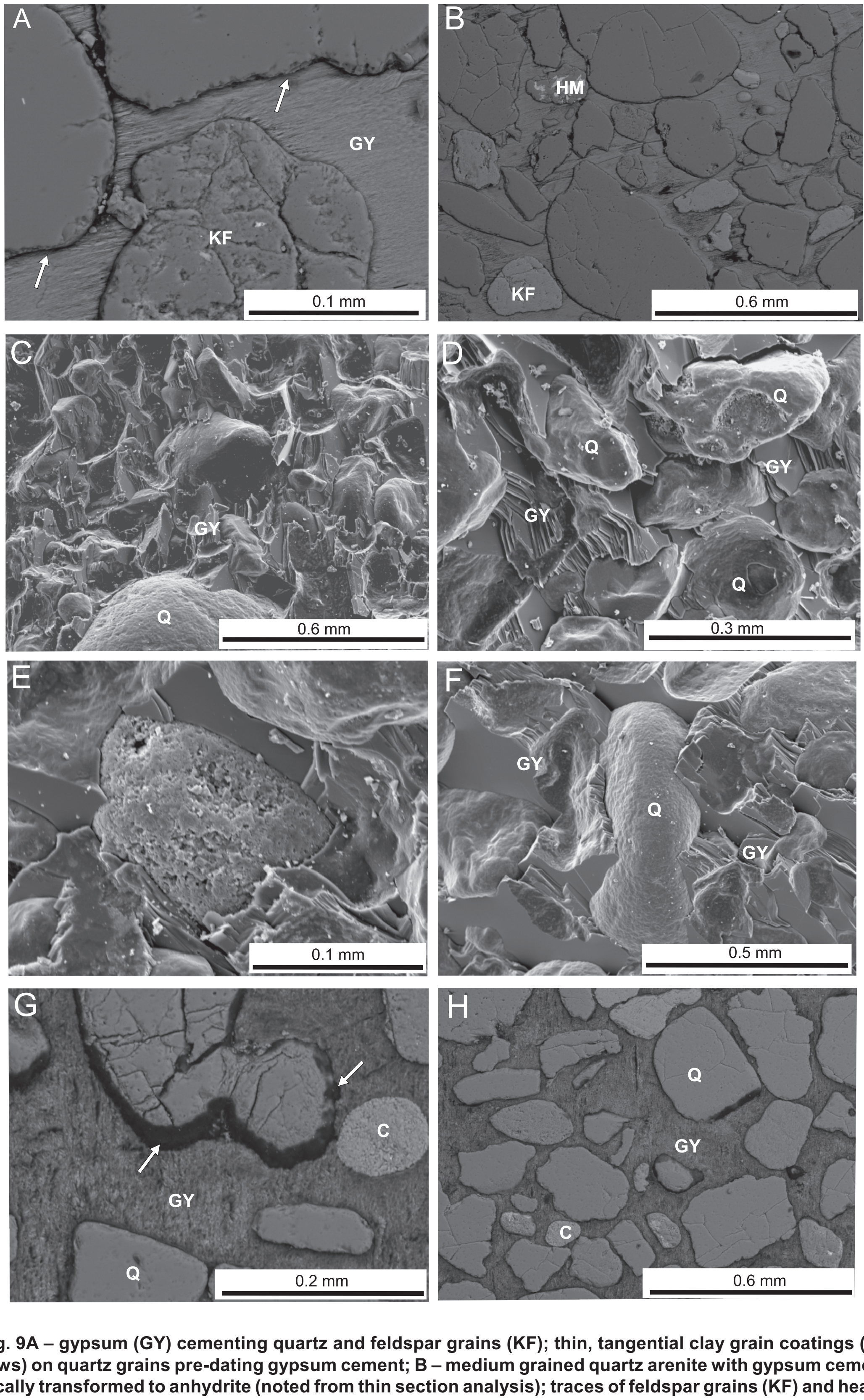

Fig. 9A – gypsum (GY) cementing quartz and feldspar grains (KF); thin, tangential clay grain coatings (arrows) on quartz grains pre-dating gypsum cement; B – medium grained quartz arenite with gypsum cement locally transformed to anhydrite (noted from thin section analysis); traces of feldspar grains (KF) and heavy minerals (HM); thin tangential clay grain coatings on quartz grains; C – medium grained quartz arenite; intergranular areas are filled by gypsum cement that is locally transformed to anhydrite; D – gypsum, showing platy/sheet-like texture, enclosing quartz grains; E – dolomite clast enclosed by gypsum cement; F – quartz grains enclosed by gypsum cement; sheet-like texture of gypsum cement; medium to coarse grained, quartz arenite; G – tangential grain coating clays pre-dating gypsum cementation (arrows); common rounded calcite grains; H – well-rounded grains; common lithic grains comprising calcite and chert; thin tangential clay coatings on grains have been engulfed by later gypsum cementation

tion. We suggest the non-pedogenic model as a mechanism for the precipitation of gypsum close to the groundwater that can provide prolonged hydrochemical stability.

The diagenetic evolution of the sand roses includes in chronological order the following processes: development of clay coatings around the sand grains, unstable grain dissolution and precipitation of poikilotopic gypsum cements from an over-saturated brine.

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