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Biofacies and diagenetic alterations of the Pleistocene coral reefs, northwest Red Sea coast, Saudi Arabia

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Middle to Late Pleistocene coral reefs stretch in three discontinuously elevated units above the present sea level between Duba and Sharma along the Red Sea coast, northwest Saudi Arabia. They correspond to MIS 5, MIS 7, and MIS 9 of the deep sea cores. Each unit exhibits prominent terraces as a result of the onlap during different sea levels, erosion during transgression, and tectonic uplift. Framestones, bafflestones, bindstones, packstones, grainstones and floatstones of coral, algal, and other bioclasts are the main microfacies types recorded from these reefal units and their internal sediment. The lower and the upper units exhibited a vertical pattern of a transgressive sequence, starting at the base with a coral assemblage of coral rock zone and graded into the upper reef slope community at the top, while the middle one exhibited a regressive sequence. Corals progressively changed from aragonite in the lower unit to calcite in the upper one by meteoric leaching of the trabeculae, and the cements changed from marine aragonitic needles and peloidal Mg-calcite in the lower unit to blocky and dog teeth cements and silica in the middle and upper units. The gravel lenses within coral colonies of the upper unit with plagioclase, epidote, and fractured quartz grains are attributed to a granitic province from the hinterland mountains, driven to the reef during rainy periods.

KEYWORDS
biofacies analysis, coral reefs, diagenetic alterations, Pleistocene, Red Sea coast, Saudi Arabia

1 | INTRODUCTION

The Red Sea provides a unique natural laboratory to study the modern-day fringing reefs along the Red Sea coast and the Middle and Late Pleistocene fossil coral terraces from interglacial periods outcropping alongside the modern ones (Casazza, 2017; Plaziat, Reyss, Choukri, & Cazala, 2008). The fossil coral terraces exhibit different elevations above the present sea level and exhibit similarities in their facies patterns (Dullo, 1990; El-Sorogy, 1997a, 1997b).

Intensive studies have been done on the Pleistocene marine terraces along the Red Sea coast and their Suez and Aqaba gulfs from different points of view, e.g., geology and biology (Behairy, Sheppard, & El-Sayed, 1992; Walther, 1888), carbonate diagenesis (Friedman, 1972; Gvirtzman, Friedman, & Miller, 1973; Gvirtzman & Friedman, 1977; Friedman & Brenner, 1977; Dullo, 1983, 1986; El-Sorogy, 1997a), fossil record and facies analysis (Alexandroff, Zuschin, & Kroh, 2016; Al-Rifaii & Cherif, 1988; Casazza, 2017; Dullo, 1984; El-Sorogy, 1997b, 2008; Manaa, 2011; Taviani, Montagna, Rasul, Angeletti, & Bosworth, 2019), palaeontology and depositional environments (Ziko & El-Sorogy, 1995; El-Sorogy, 2002; Mandurah, 2010; Khalil, 2012), and environmental geology (Abd El-Wahab & El-Sorogy, 2003; El-Sorogy, Abdelwahab, & Nour, 2012; El-Sorogy, Nour, Essa, & Tawfik, 2013).

Since little is known on the paleontological content of Pleistocene terraces along the Saudi Red Sea coast and these terraces host a remarkable paleobiological legacy, which is useful to unravel biogeographic connections, to reconstruct former environments, to disclose paleoclimatic events, and recognize past biodiversity, therefore, the main targets of the present work are to use field description, fossil content; especially, scleractinian corals, as well as thin sections, to document the biofacies and diagenetic alterations of the Pleistocene coral reefs along the Red Sea coast, Saudi Arabia.

2 | MATERIALS AND METHODS

Intensive field descriptions and fossil and rock samples were collected from the Pleistocene terraces between Duba and Sharma along the Red Sea coast, Saudi Arabia. These reef terraces were studied in 10 localities, mostly at wadis (erosional valleys), which running perpendicular to the coast form breaks in the terraces allowing access to the outcrop face (Figure 1): location 1 (27° 30′ 04“N and 35° 75’ 07”E), location 2 (27° 34′ 32“N and 35° 69’ 62”E), location 3 (27° 35′ 40“N and 35° 67’ 45”E), location 4 (27° 38′ 39“N and 35° 64’ 23”E), location 5 (27° 41′ 62“N and 35° 61’ 15”E), location 6 (27° 42′ 01“N and 35° 60’ 98”E), location 7 (27° 48′ 69“N and 35° 56’ 85”E), location 8 (27° 64′ 00“N and 35° 49’ 92”E), location 9 (27° 65′ 30“N and 35° 48’ 92”E), and location 10 (27° 78′ 52“N and 35° 39’ 88”E). The lower reef unit was described and sampled from the 10 localities, the middle unit from seven localities, whereas the upper unit was described and sampled from two localities; 51 thin sections were prepared for microfacies analyses and coral identification in the Faculty of earth Sciences, King Abdul-Aziz University, Saudi Arabia. Due to high porosity of coral samples, they were impregnated with resin under vacuum. Thin sections are investigated and photographed using polarizing microscope. The classification of carbonate rocks followed the nomenclature of Dunham (1962), Embry and Klovan (1972), and the energy index classification of Plumley, Risley, Graves, et al. (1962).

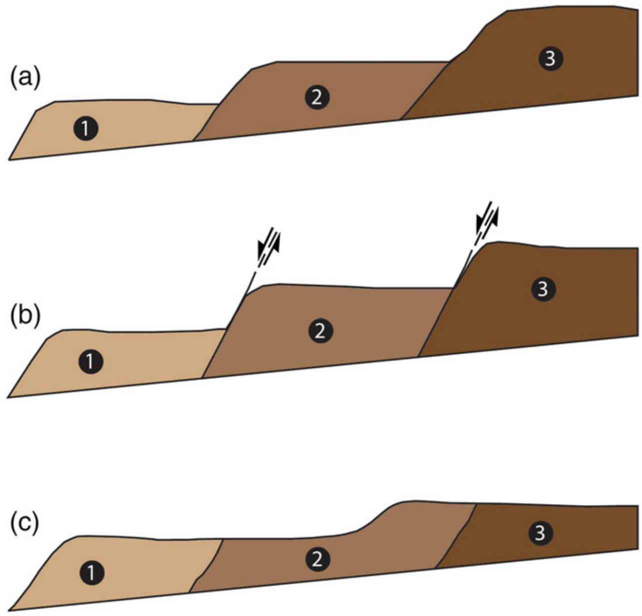

FIGURE 2 Three possibilities of morphological terraces. (a) Constructive onlap during different sea levels. (b) Block faulting by tectonics. (c) Different erosive planations. 1–3 = three different reef units in age (modified after Dullo, 1990) [Colour figure can be viewed at wileyonlinelibrary.com]

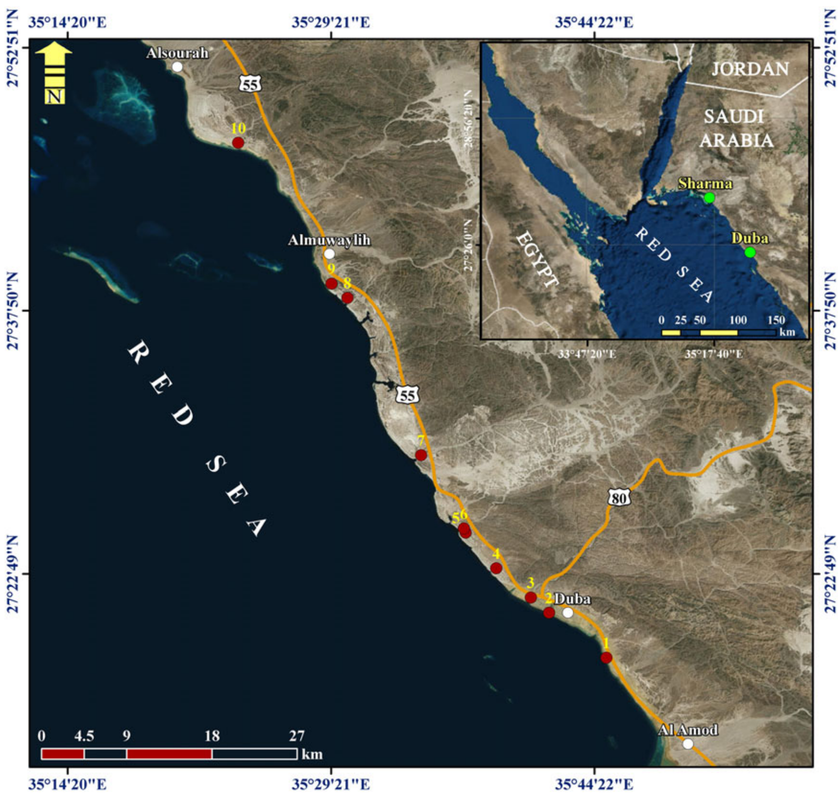

FIGURE 1 Location map of the studied Pleistocene reefal units [Colour figure can be viewed at wileyonlinelibrary.com]

3 | RESULTS AND DISCUSSION

3.1 | Field investigation and biofacies analysis

The coastal strip along the Red Sea is wide. The Quaternary sediments vary in thickness and in size of the area they cover. Morphologically, the coastal plain comprises also Precambrian basement and tilted marine Tertiary sequences (Dullo, 1990; Hotzl, 1984). The basement rocks north of Duba reaches almost to the present coast, leaving only a plain 1–3 km wide formed by sediments. The marine strata of Quaternary age are restricted to a strip of 500–800 m width. Pleistocene fringing reefs were developed along the coasts of the Red Sea during interglacial high stands (El Moursi, Hoang, El Fayoumy, Hegab, & Faure, 1994; Plaziat et al., 1998). On the Saudi coast, between Duba and Sharma, Middle and Late Pleistocene terraces appear as three obvious units. Dullo (1990) stated three possibilities for the Pleistocene morphological terraces: constructive onlap during different sea levels, block faulting by tectonics, and different erosive planations (Figure 2). The idealized sequence of the studied reefal units is shown at Wadi Gfafa, 3 km south of Duba (Figure 3). The following is a

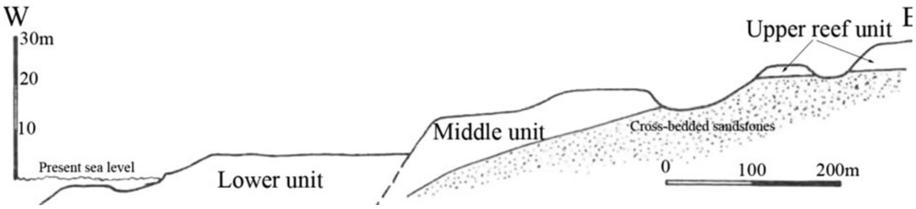

FIGURE 3 Sequence of the three reefal units at Wadi Gfafa, locality 1 (modified after Dullo, 1990)

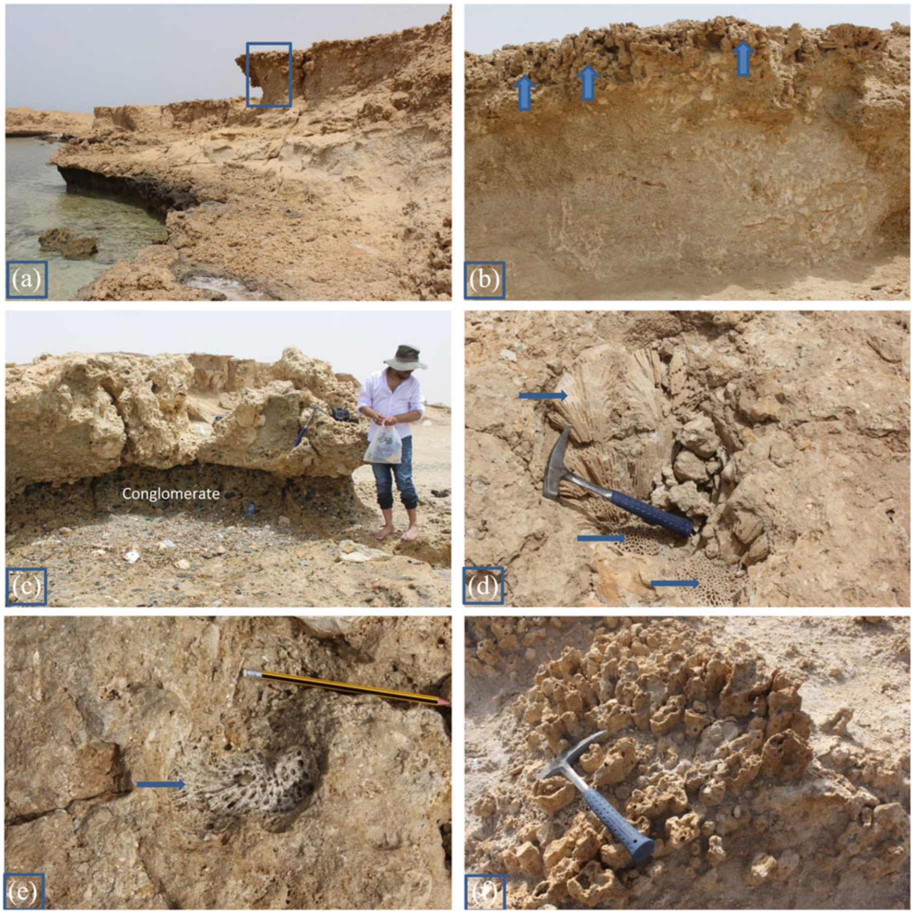

FIGURE 4 (a) Lower reef unit at locality 5. The small planation in 1.5 m above present sea level is the result of the Flandrian transgression. (b) Enlarged part of Figure a (rectangle) showing graduation from lagoonal in the bottom (packstone and grainstone) to upper reef slope (framestone) with columnar colonies of *Porites* in the top (arrows). (c) Fossil wave notch in the lower reef unit overlays a conglomeratic bed of basement clasts, indicating a transgressive pattern (locality 6). (d, e) Small microatoll consisting of framestone and bindstone with *Favia* colonies (arrows) and coralline red algae. Lower unit, locality 7. (f) Framestone with columnar colonies of *Porites*, which exhibit numerous borings of *Vermetus*, lower unit, locality 9 [Colour figure can be viewed at wileyonlinelibrary.com]

detailed description about the biofacies, elevations, vertical pattern, microfacies assemblages, and the suggested causes for the morphological steps of the studied reef terraces.

3.1.1 | Lower reef unit

The lower (youngest) reef unit exhibits two prominent terrace plains, different in elevation along the coastal cliffs in the study area (1.5–3 m and 8–10 m) above present sea level (Figures 4a, b). Small-scaled changes of sea level (paracycles) are responsible for the formation of these reef terraces (Vail, Hardenbol, & Todd, 1984). Also, Mathews (1984) indicated that the cycles of the lower Pleistocene reef unit at Barbados are related to sea level highstands. Its current elevation may be close to its original elevation like those studied along the Egyptian Red Sea coast by Plaziat et al. (2008), which is attributed to the stability of the study area from tectonically point of view over the Late Pleistocene. Similar reef terraces of the lower unit has been dated of 110,000 ± 8,000 years B.P. at the southern tip of Sinai Peninsula, around 123,000 years B.P. along to the Egyptian Red Sea coast, 91,000 ± 5,000 years along the Sudanese coast, 91,000 to 112,000 years at the Saudi Red Sea coast, from 141,000 to 161,000 years for corals at the same level in southern Sinai, and from 125,000 to 138,000 years on Zabarged Island (Berry, Whiteman, & Bell, 1966; Dullo, 1990; Gvirtzman & Friedman, 1977; Gvirtzman, Kronfeld, & Buchbinder, 1992; Hoang & Taviani, 1991; Plaziat et al., 2008). These ages of similar reef unit indicated that, the lower unit has been built during the last interglacial times (oxygen isotope stage 5 of deep sea cores).

The lower unit rests on a conglomeratic bed 0.75- to 1-m thick of basement clasts (Figure 4c) and exhibits a well-developed onlap onto the middle reef unit. The lower terrace include small- to medium-sized colonies (Figure 4d,e) of scleractinins (*Stylophora pistillata*, *Porites lutea*, *Favia pallida*, *Pocillopra damicornus*, *Favites pentagona*, *Galaxea fasicularis*), bivalves (*Anadara antiquata*, *Circe rugifera*, *Glycymeris pectunculus*, *Anodontia edentula*, *Chama aspersa*, *Alectryonella plicatula*, *Codakia* sp., *Cardita* sp., *Tridacna* sp.), gastropods (*Lunella coronata*, *Nerita textilis*, *Clanculus pharaonius*, *Patella flexuosa*, *Turbo* sp.), and the large echinoid spines of the sea urchin *Heterocentrotus*. In the supratidal area, the lower terrace acts as hard substrate for many living fixed molluacs and crustaceans (*Clypeomorus persicus*, *Patella flexuosa*, *Planaxis sulcafus*, *Chiton* sp., *Balanus* sp.). Gravels, shell

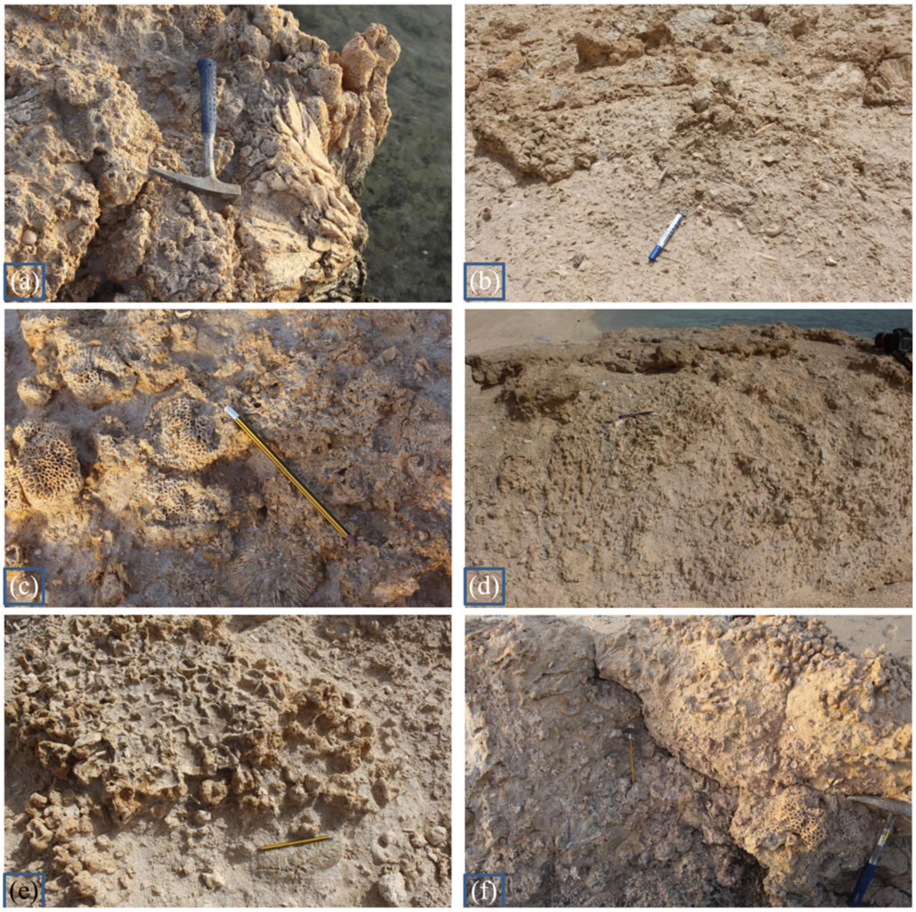

FIGURE 5 (a) Framestone with *Lobophyllia*, *Favites*, *Galxea*, *Echinopora*, and molluscan shells in the lower unit, locality 10. (b) Rudstone with molluscan accumulation and large echinoid spines of the sea urchin *Heterocentrotus* locality 6. (c) Framestone with *Favites*, *Fungia*, and molluscan shells in the lower reef unit, locality 10. (d) Bafflestone with *Millepora* of the reef crest, lower unit, locality 8. (e) Framestone with *Millepora*, *Porites*, *Ctenactis*, and the thick spines of the sea urchin *Heterocentrotus* in the lower reef unit, locality 9. (f) Bindstone with *Favia*, *Galaxea*, *Porites*, *Pocillopora*, *Fungia*, and molluscan shells (*Conus*, *Plicatula*, *Barbatia*, *Circe*, *Cypraea*, *Spondylus*) in the lower unit. All bound with coralline red algae, locality 3 [Colour figure can be viewed at wileyonlinelibrary.com]

accumulation, and algal crusts may be present in the internal sediments within coral colonies.

Coral colonies range from small to very large size in the upper terrace of the lower unit (Figure 4f and Figure 5a–f) and represented by *Porites columnaris*, *Porites lutea*, *Porites solida*, *Platygyra dedalaea*, *Leptoria phrygia*, *Galaxea fasicularis*, *Favites pentagona*, *Pocillopora damicornis*, *Acropora pharaonis*, *Favia pallida*, *Favia speciosa*, *Coscinaria monile*, *Leptastrea purpurea*, *Turbinaria mesentrins*, *Echinopora gemmacea*, *Goniastrea pectinata*, *Fungia fungites*, *Fungia granulosa*, *Lobophyllia carymbosa*, *Ctenactis echinata*, and the milleporids *Millepora dichotoma*, *Millepora platyphyllia*. Red algae act as adhesive factor for coral and milleporid colonies, which are mostly bored by *Vermetus maximus*. The other invertebrate fossils are represented by *Dosinia radiata*, *Tridacna squamosa*, *Cypraea* sp., *Spondylus hystrix*, *Alectryonella plicatula*, *Callista florida*, *Trapezium sublaevigatum*, *Ostrea* sp., *Conus ardisiaceus*, *Strombus gibberulus*, *Hexaplex kuesterianus*, *Barbatia* sp., *Plicatula* sp., and regular echinoid spines.

Thin sections from the lower unit gave the following microfacies types: coral framestone, algal coral bindstone, algal coral framestone, bioclastic bafflestone, bioclastic rudstone, and bioclastic grainstones (Figure 8a–e). Skeletons of different corals and coralline red algae (*Lithothamnium* and *Lithophyllum*) act as frame builder and frame binder, respectively. Other skeletal grains like corals, foraminifers, gastropods, bivalves, and echinoids debris act as essential rock forming constituents. Most cavities are bounded by sparry calcite cements. The depositional interpretations are easy to trace in the lower reef unit in comparison with those in the middle and upper ones due to presence of numerous exposures of the lower unit along coastal cliffs and wadi cuts, its well-preserved fossil content or less effected from diagenesis point of view and the few exposures of the middle and upper units, which may be covered with wadi sediment. The lower reef unit exhibits a vertical pattern of a transgressive sequence. It shows a deepening upward development, starting at the base with a coral assemblage of coral rock zone and overlaid by reef crest facies, which grades into the upper reef slope community. This deepening upward facies development indicates increasing water depth, which was controlled by a combination of changes in sea level, subsidence rate, and sediment accumulation (Strasser, Strohmenger, Davaud, & Bach, 1992).

3.1.2 | Middle reef unit

The middle (intermediate) reef unit rises 12 m above present sea level at its seaward edge (Figure 6a–f). In some coastal cliffs, the lower reef

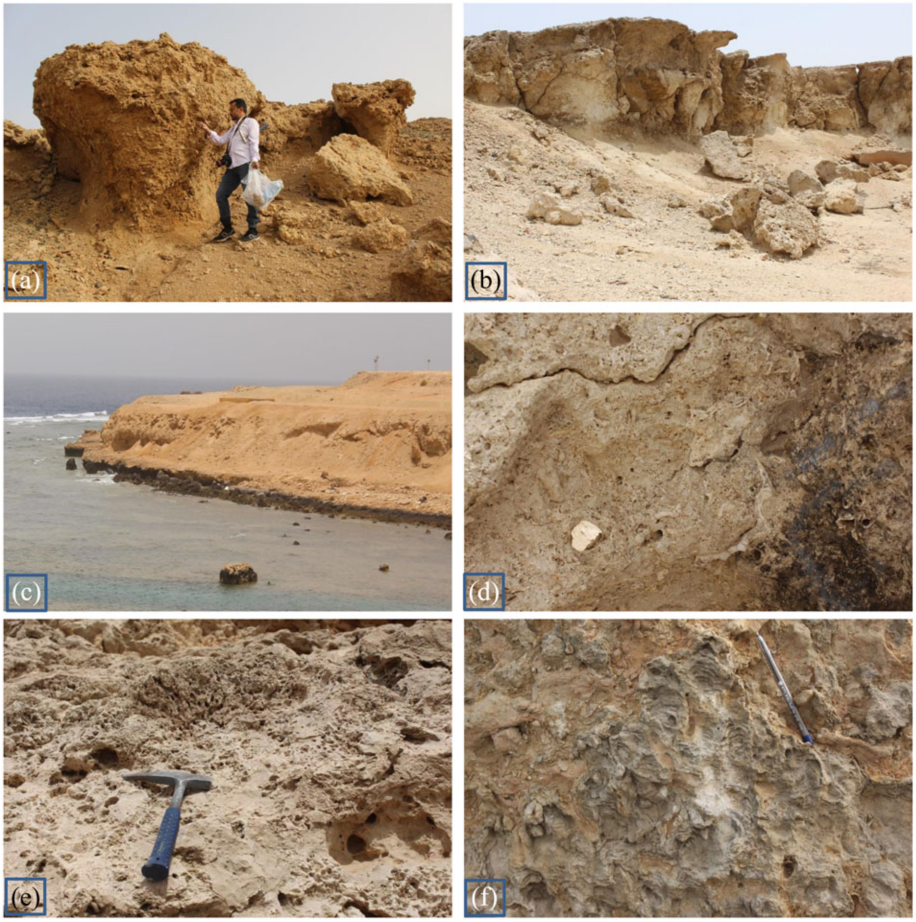

FIGURE 6 (a, b) Middle reef unit, Wadi Gfafa, locality 1. (c) Middle unit onlap to middle unit, locality 6. (d) Rudstone with coralline algae, coral fragments, and bivalves (*Tridacna* sp.), locality 6. (e) Framestone with *Millepora*, which is bored with *Vermetus maximus* in the Middle reef unit, locality 7. (f) Framestone with massive colony of *Porites lutea* in the Middle reef unit, Wadi Gfafa, locality 1 [Colour figure can be viewed at wileyonlinelibrary.com]

unit onlaps onto the middle reef one (Figure 6c), and in other localities, the middle reef unit may be eroded down to the level of the lower reef unit (5–6 m). Like the lower unit, the current elevation of the middle one is close to their original elevation. It had an age ranging from 200,000 to 250,000 years B.P., from in south Sinai Peninsula, from 170,000 to 250,000 years in southern Sinai, 200,000 years from Zabarged Island and 205,000 years along the Saudi Red Sea coast (Gvirtzman & Friedman, 1977; Gvirtzman et al., 1992, Hoang & Taviani, 1991; Dullo, 1990). Accordingly, the studied unit is compared with the Oxygen isotope stage 7 of the deep sea cores.

The middle unit is composed of two elevated terraces, in spite of it is difficult to distinguish the two terraces in some localities. The lower terrace is 2.5- to 3-m thick of massive coralline limestone with moderately to badly preserved corals and milleporids of *P. lutea*, *Favites pentagona*, *Favia pallida*, *Echinopora lamellosa*, *Goniastrea pectinata*, *Leptastrea*, *Millepora platyphylla*. Most are bored by *Vermetus maximus*. Molluscans are represented by *Saccostrea cuccallata*, *Codakia tigerina*, *Circe intermedia*, *Dosinia contracta*, *Tridacna* sp., *Glycymeris pectunculus*, *Nassarius persicus*, *Ancilla castanea*, *Bulla ampulla*, and other gastropod moulds. The upper terrace of the middle unit is 3- to 4.5-m thick of yellowish white reefal limestone. Most corals are of badly preserved dendroid and branched growth forms of *Stylophora*, *Pocillopora*, *Acropora*, in addition to massive *Porites*. Internal moulds of gastropods and bivalves are also present. Coralline algae bind all skeletal particles.

This unit gave the following microfacies types: algal coral bindstone, bioclastic grainstone, algal coral packstone, coral bafflestone, and coral framestone (Figure 8f and Figure 7a,b). The alga *Lithothamnium* binds other skeletons of corals, foraminifers, sponge spicules, and fragments of bivalves and echinoids. The cavities are bounded by acicular cements. Some coral cavities are filled with internal sediments of lime mud, few quartz grains, and fossil fragments. The nonskeletal grains include few plagioclase, quartz. The middle reef unit exhibits a vertical pattern of a regressive sequence. It starts with coral community of upper reef slope community, followed with reef crest and then grades regressively to coral rock zone facies. Finally, it is overlain with wadi sediments.

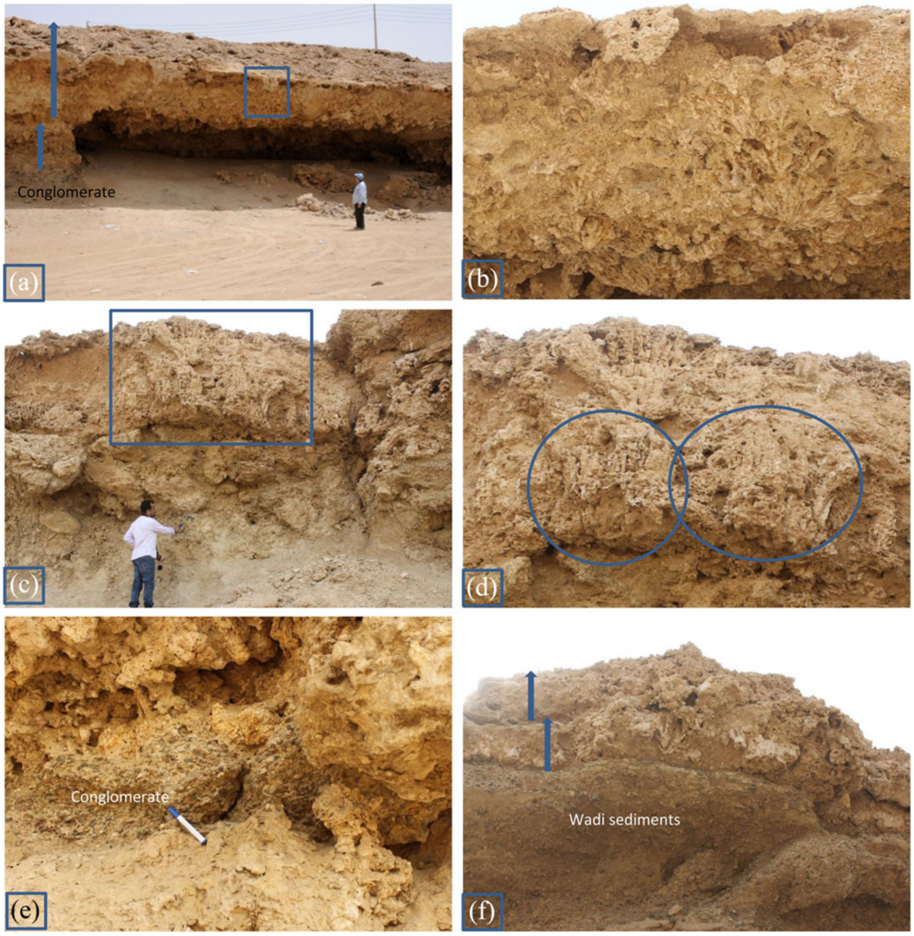

FIGURE 7 (a) Upper reef unit occur in two elevated levels above conglomeratic bed in locality 7. (b) Enlarged part of Figure a (rectangle) showing bafflestone with dendritic corals of *Pocillopora*, *Acropora*, *Stylophora* in the upper terrace of the upper unit, locality 1. (c) Upper reef unit occur in two elevated levels in Wadi Gfafa, locality 1. (d) Enlarged part of Figure c (rectangle) showing large columnar coral colonies of *Porites* in the upper terrace. The overturned colonies may be related crushed as result of intensive terrigenous influx due to heavy rain period, locality 1. (e) Conglomeratic clasts and gravel lenses within coral colonies of the upper reef unit, Wadi Gfafa, locality 1. (f) Upper unit occurs in two elevated levels above wadi sediments, Wadi Gfafa, locality 1 [Colour figure can be viewed at wileyonlinelibrary.com]

3.1.3 | Upper reef unit

The upper (oldest) reef unit is developed at 20 to 30 m above present sea level, farther inland, in Wadi Gfafa, 3 km south of Duba (locality 1) and in locality 7 (Figure 7a–f). This high elevation is attributed to sea-level change and tectonic uplift (Gvirtzman & Friedman, 1977; Plaziat et al., 2008) like the oldest reef along the Gulf of Aqaba, where the reef terraces occur several meters higher than they were at the time of reef formation (Dullo, 1990; Lambeck et al., 2011). This unit could be compared with that dated over 300,000 years bp along the Egyptian Red Sea coast and from 330,000 to 290,000 years for corals in the same stratigraphic levels in southern Sinai (Gvirtzman et al., 1992; Plaziat et al., 2008), which probably corresponds to the oxygen isotope stage 9 of the deep sea cores.

The upper reef unit frequently occurs on top of isolated inselbergs without an onlap contact with the middle reef unit (Figure 7a,c,f). In locality 7, it rests on conglomeratic bed, 1.5-m thick and composed of two elevated steps 2 m and 3 m (Figure 7a). In Wadi Gfafa, the upper unit rests on massive very hard algal limestone rich in pectinids and irregular sea urchins (may be of Tertiary age) and also formed of two elevated steps, 3.5 m and 2.5 m. In some areas within Wadi Gfafa, the upper unit rests on wadi sediments and upon gravely, cross-bedded sandstone with sharp contact between them. In all exposures of upper reef unit in wadi Gfafa, there are gravel lenses and cobbles of basement origin within and among coral colonies (Figure 7e,f) indicating heavy rain periods, which carried these basement materials from hinterland mountains to the reef environment.

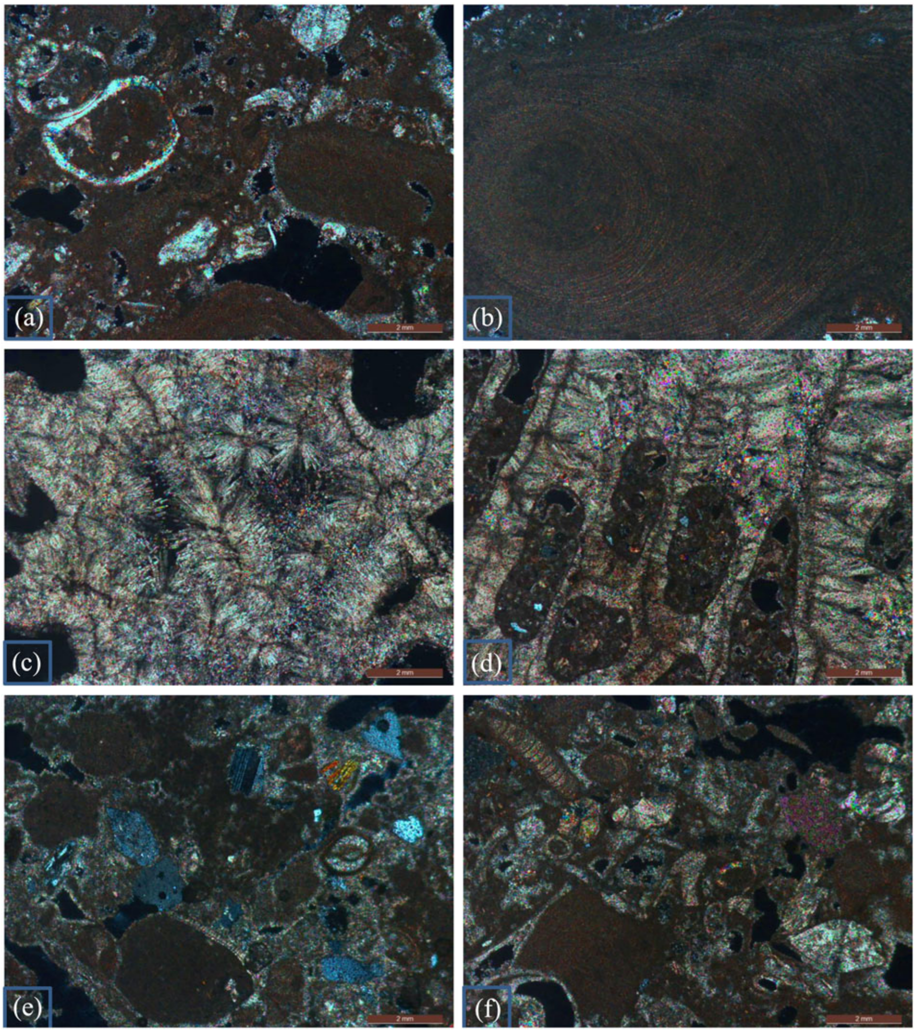

FIGURE 8 (a) Algal bindstone, the red algae acts as frame-binder for corals, gastropods, foraminifers, bivalves, echinoids. All cavities are bounded by sparry calcite cements. Lower unit, locality 8. (b) Algal coralline bindstone, skeleton of the red algae, *Lithothamnium* act as frame builder between coral skeletons. Lower unit, locality 8. (c) Skeleton of *Cyphastrea* shows marine cements in the form of aragonite needles as marine cements in the pore spaces and the initial stage of leaching trabeculae. Lower unit, locality 7. (d) Coral skeleton is formed of aragonitic clusters, with peloidal Mg-calcite, few quartz grains, and fossil fragments within coral cavities. Lower unit, locality 2. (e) Algal coralline packstone, with skeletal grains of *Lithothamnium* algae, corals, foraminifers, bivalves, brachiopods, and echinoids. The nonskeletal grains include few plagioclase, epidote, and quartz. All embedded in microsparite cements. Middle unit, locality 6. (f) Algal coralline packstone with fragments of *Lithothamnium* and *Lithophyllum* algae, corals, foraminifers, bivalves, brachiopods, and echinoids. Middle unit, locality 2 [Colour figure can be viewed at wileyonlinelibrary.com]

The lower terrace is hard coralline limestone with badly preserved corals of *Stylophora*, *Porites*, *Favia*, *Pocillopra*, *Favites*, *Galaxea*), bivalves (*Anadara uropigimelana*, *Codakia*, *Cardita* sp., *Circe rugifera*, *Glycymeris pectunculus*, *Tridacna* sp.), gastropods (*Turbo*, *Nerita*, *Patella* spp.). About 70% of the coral colonies in the upper terrace is represented by the columnar growth form *Porites columnaris* (Figure 7c,d). The others are of *Pocillopora damicornis*, *Acropora pharaonis*, *Lobophyllia carymbosa*, and the milleporids *Millepora dichotoma*. Red algae act as adhesive factor for coral and milleporid colonies, which are intensive bored by *Vermetus maximus*. Internal moulds of gastropods and bivalves are also present.

The upper unit yielded coral framestone, coral bafflestone, algal coral bindstone, bioclastic rudstone in its thin sections investigation (Figure 9c–f). Thin sections in the internal sediments of the gravel lenses among coral colonies gave bioclastic floatstone and bioclastic packstone with lithoclasts of orthoclase, plagioclase epidote, and fractured quartz grains (indicating granite province), came from hinterland during rainy periods and mixed with marine taxa of red algae corals and foraminifers. All embedded in micritic matrix. The upper reef unit exhibits a similar lateral facies development of the other reef units, but it shows a vertical pattern of a transgressive sequence similar to the lower unit. The whole sequence of the upper unit is a transgressive and shows again a deepening upward development like the lower unit. Also, it is overlain with alluvial sands and gravels.

3.2 | Diagenetic alterations

Investigation of thin sections conducted from the different studied reef units illustrated a progressive sequence of diagenetic alterations.

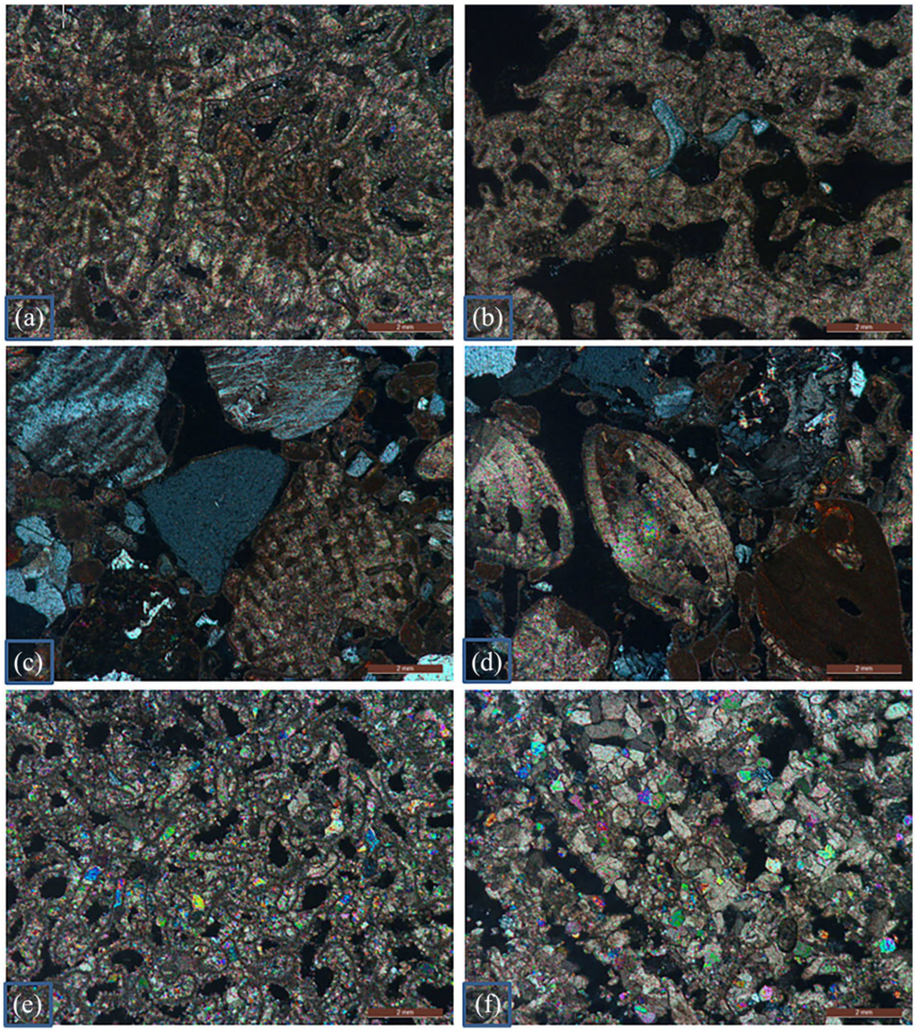

FIGURE 9 (a) Coralline framestone. Most skeleton of *Porites* shows increasing leaching of the trabecular structures, and the coral cavities are filled with blocky calcite cements. Some cavities in the lower part of the photo are still filled with aragonitic marine cements skeleton. Middle unit, locality 2. (b) Same skeletal features of Figure a, in addition to silicification in the central part. Middle unit, locality 7. (c, d) Bioclastic floatstone with corals, red algae, foraminiferal tests, orthoclase, epidote, and fractured quartz grains. All embedded in micritic matrix. Upper unit, locality 1. (e, f) Coralline framestone with complete change of *Porites* and *Galaxea* skeletons respectively to calcite. The remnants of skeleton are shown in the form of dark micritic lines. Most coral cavities are filled with blocky and dog teeth cements. Upper unit, Wadi Gfafa, locality 1 [Colour figure can be viewed at wileyonlinelibrary.com]

Skeleton of *Cyphastrea* from the lower unit shows primary microstructure and presence of aragonite needles or rods as marine cements in the pore spaces, syntaxially grown on the trabecular structure (Figure 8c,d). Also, micritic envelopes and peloidal Mg-calcite are detected within parts of the coral skeleton. Bathurst (1971) attributed the formation of the micritic envelopes to the dissolution and reprecipitation of carbonate on the micron scale along perforations of endolithic organisms. An initial stage of diagenesis in the form of early meteoric leaching on the trabecular structure, which results in dissolving and open trabecular centers (Figure 8d). This diagenetic pattern occurs especially in the upper terrace of the lower reef unit. It may be related to superficial run-off related to intergranular water movement. The coral cavities are filled with internal sediments of lime mud, few quartz grains, and fossil fragments. Most of the *Porites* skeleton is changed from aragonite to calcite. The remnants of skeleton are shown in the form of dark micritic lines. About 90% of the coral cavities are filled with blocky calcite cements, with few aragonite cements. The cryptocrystalline high-magnesium calcite and aragonite cement strongly suggest that early cementation occurred exclusively under marine environment (Folk, 1974). Stable isotopes of samples from the same level along the Egyptian Red Sea coast gave values ranging from +0.33%0 δ^{13}C PDB to +2.10%0 δ^{13}C PDB and from −3.28%0 δ^{18}O PDB to −2.37%0 δ^{18}O PDB (El-Sorogy, 1997a, 1997b). These isotope values indicate a typical normal marine limestone (Hudson, 1977) and are comparable with the data obtained from the youngest unit from southern Sinai and Saudi Red Sea coast (Strasser et al., 1992; Dawood, Aref, Mandurah, Hakami, & Gameil, 2013).

Coral skeletons of the middle unit are characterized by increasing leaching of the trabecular structures, which is already replaced by calcite, in comparison with the lower unit. All skeletal elements of the coral *Galaxea* and *Porites* (walls, septa, dissepiments, and synapticulae) are recrystallized (Figure 9a). Most of the cavities are filled with blocky and dog teeth cements, which grow on the micritic envelops and reduce the porosity. Dogtooth cement provides the best evidence that cementation has occurred within air-filled marine environment (Longman, 1980). Other few cavities show silicification, which is the secondary filling of pore spaces with fine-grained quartz, chalcedony, or opal (Figure 9b). This process was recently discussed on completely silicified free specimens of the upper Cretaceous rudists in northwestern Jordan and Saudi Arabia (Özer & Ahmad, 2016; Özer, El-Sorogy, Al-Dabbagh, & Al-Kahtany, 2019). The middle unit is also characterized by an intense leaching of most of the other biota, especially of aragonitic mineralogy and an increased cementation by blocky calcite. Stable isotopes of samples from the same level along the Red Sea coast of Egypt gave values ranging from +0.10%0 δ^{13}C PDB to +2.41%0 δ^{13}C PDB and from −5.46%0 δ^{18}O PDB to −2.90%0 δ^{18}O PDB (El-Sorogy, 1997a, 1997b). These isotope values indicate the bulk range of marine limestone, with a distinct fresh water signal.

Coral skeletons of (*Porites* and *Galaxea*) from the upper unit are characterized by a completely altered microstructure (Figure 9e,f). Skeletal grains and cements were selectively dissolved and reprecipitated in situ as a sparry calcite mosaic, and only rare tiny relics of aragonite needles of the former coral skeleton are found as inclusion within the low magnesium calcite. In most cases, only the micrite envelopes preserve the outline of the original corallities. The upper reef unit also is characterized by a continuous reduction of biogenic skeletons due to leaching. The equant calcite spar (low magnesium calcite) lining or completely filling the primary and secondary voids or replacing earlier aragonite skeletal grains, leads to decrease porosity. Samples from the same level along the Egyptian Red Sea coast gave stable isotope values ranging from −2.75%0 δ^{13}C PDB to −1.34%0 δ^{13}C PDB and from −9.20%0 δ^{18}O PDB to −5.44%0 δ^{18}O PDB (El-Sorogy, 1997a, 1997b). These negative isotope values indicate a strong fresh water influence and are comparable with the data of the oldest reef from the southern Sinai (Strasser et al., 1992) and with Pleistocene limestones of Enewetak atoll, western Pacific Ocean (Saller & Moore, 1991).

4 | CONCLUSIONS

Field investigation indicated three Pleistocene reefal units in different elevated levels above the present sea level, along the Red Sea coast, northwest Saudi Arabia. The onlap during different sea levels, erosion during transgression, and tectonic uplift are the three possibilities for the morphological steps in the reef units. The lower unit exhibited two terrace plains and gave coral framestone, algal coral bindstone, bioclastic bafflestone, bioclstic packstone, and algal coral framestone as microfacies types. It exhibited a vertical pattern of a transgressive sequence or a deepening upward development, and their coral samples showed aragonitic microstructure and marine cements in the form of aragonitic needles, micritic envelopes, and peloidal Mg-calcite. Some initial stages of diagenesis in the form of early meteoric leaching on the trabecular structure were noticed in few samples. The middle unit composed of two elevated terraces and yielded algal coral bindstone, algal coral packstone, bioclastic bafflestone, and coral framestone from thin section examination. It exhibited a vertical pattern of a regressive sequence, and their coral skeletons are characterized by increasing leaching of the trabecular structures, which is already replaced by calcite. Most of the cavities are filled with blocky and dog teeth cements, other voids showed silicification. The upper unit is developed on top of isolated inselbergs without an onlap contact with the middle unit. It composed of two elevated steps and yielded coral framestone, bioclastic rudstone, bioclastic bafflestone, and algal coral bindstone. Thin sections in the gravel lenses among coral colonies gave bioclastic floatstone and bioclastic packstone with lithoclasts came from hinterland during rainy periods. Its whole sequence is a transgressive, and their corals showed completely alteration.

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