

COMPOSITION AND MORPHOLOGY OF EARLY DEVONIAN MICROBIAL AND METAZOAN PATCH REEFS: QASR MEMBER OF THE JAUF FORMATION, NORTHWESTERN SAUDI ARABIA

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ABSTRACT: Late Pragian–early Emsian (~ 405 Ma) microbial and metazoan reefs in the Al-Jawf area of northwestern Saudi Arabia occur in the 20-m-thick Qasr Limestone Member of the Jauf Formation, within a dominantly fine-grained marine siliciclastic sequence deposited on a broad shelf adjacent to the Arabian–Nubian Shield. Microbial reefs, composed of stromatolites, thrombolites, and to a lesser extent leiolites, are circular to elliptical in plan and have mounded-domical cross sections. Individual microbial reefs up to 6 m in height and 15 m across are commonly laterally and vertically juxtaposed in composite buildups up to 10 m high and 60 m across. Metazoan reefs, dominated by poorly preserved bryozoans, range from small subcircular mounds 10–60 m across, through ridges up to 300 m in length, to more complex structures and reach 4 m in height. The Qasr Member provides a rare example of well-exposed Early Devonian reefs in plan view. Satellite images show the spatial arrangement of Qasr mounds as hundreds of small patch reefs over a wide area. Regardless of type, the reefs and composite bioherms are generally NNE–SSW-oriented and many are grouped into parallel rows. This pattern, as in some modern patch-reef complexes, may reflect direct influence of paleotopography and water circulation patterns. The reefs are enclosed and separated by bedded deposits, marls, siltstones, and limestones: intraclastic floatstones, bioclastic floatstones–rudstones, and peloidal grainstones. The Qasr reef complex probably developed in generally low-energy environments between normal and storm wave base, in turbid to clear water. Early Devonian increase in microbial reefs, such as Qasr, challenges the view that post-Cambrian stromatolites were common only in normal marine subtidal settings in the wake of metazoan mass extinctions.

INTRODUCTION

Reefs commonly containing stromatoporoid sponge and tabulate coral skeletons, together with microbial carbonates, were often widespread, diverse, and abundant from the mid-Ordovician to early Late Devonian (Copper 1974, 1994; Fagerstrom 1987). During this extended interval, development of skeletal reefs declined during the Ordovician–Silurian transition and again near the Silurian–Devonian transition (Wilson 1975; Copper 1994). Fagerstrom (1987) drew attention to Late Silurian–Early Devonian decline in reef size and abundance and in stromatoporoid species diversity. Data compiled by Kiessling (2002) also suggest that Early Devonian reefs were less abundant and more microbial than those immediately before and after. The Late Silurian–early Emsian has therefore been regarded as an “extended reef crisis” (Flügel and Kiessling 2002) that lasted 10–15 My.

The Early Devonian of the Arabian Peninsula is generally siliciclastics-dominated. An exception is the carbonate Qasr Member of the Jauf Formation in northwestern Saudi Arabia, which contains the reefs described here which developed towards the end of this Late Silurian–Early Devonian interval. Although their largely dolomitized (Bahafzallah et al. 1981) fabrics are poorly preserved, these Qasr reefs are spectacularly exposed, revealing the geometry of the entire reef complex as well as of individual reefs, including cross sections, vertical arrangement, and contacts with lateral facies. Here we describe the structure, dimensions, shape, and spatial arrangement of these buildups and assess the

environmental parameters that controlled their growth. The patterns of reef distribution are directly comparable with those in modern coral patch reefs on shallow platforms. Qasr reefs were initially described as coral deposits (Helal 1965). Here we show that they are dominantly microbial (stromatolitic) and are associated with relatively diverse coeval metazoan inter-reef biotas. As has been pointed out in other studies of reefs near the Silurian–Devonian transition (Soja 1991; Soja et al. 2000), this microbial–metazoan association raises questions concerning controls on microbial carbonate development, and challenges the view that post-Cambrian stromatolites were common only in normal marine subtidal environments in the wake of metazoan mass extinctions. The biotic composition of Qasr reefs underscores the need for a more nuanced interpretation of these broad geobiological relationships.

GEOLOGICAL SETTING

Paleogeographic reconstructions for the Early Devonian (Golonka 2002; Scotese 2003) show the Arabian Peninsula region as part of Gondwana’s northern passive margin, situated ~ 40–50° south of the paleoequator and rotated about 20° anticlockwise from its present position (Fig. 1A). Much of the area northeast of the Arabian–Nubian Shield was covered by an epeiric sea (Al-Laboun and Walthall 1988; Konert et al. 2001). The shoreline approximately followed the margin of the shield, although its precise position remains uncertain, mainly as a

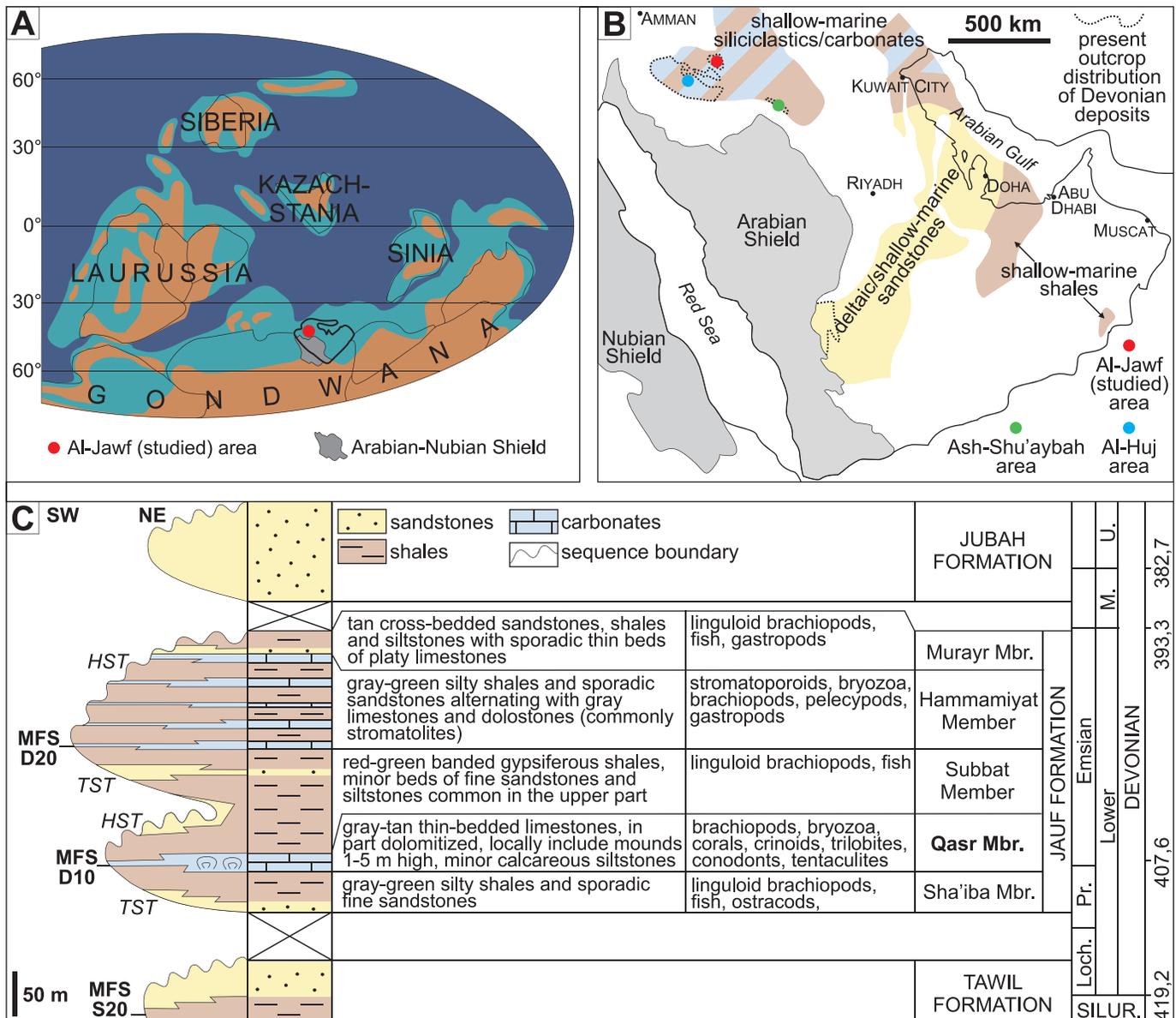


FIG. 1.—A) Paleogeographic position of the Al-Jawf area in the Early Devonian; simplified and compiled from Copper (2002), Golonka (2002), and Scotese (2003). B) Generalized paleofacies map for the Devonian of the Arabian Peninsula (mostly subcrop view). A large delta front in eastern Saudi Arabia was replaced northward by mixed marine siliciclastics and carbonates; compiled from Konert et al. (2001) and Al-Laboun and Walthall (1988). C) Generalized stratigraphic column for the Devonian in the northwestern Arabian Peninsula. The Jauf Formation (Pragian–Emsian) represents two subsequent third-order transgressive–regressive pulses. Simplified, modified and compiled from Al-Hajri et al. (1999), Sharland et al. (2001), and Haq and Al-Qahtani (2005). Radiometric ages are from Gradstein et al. (2012).

result of Variscan (Hercynian) uplift and erosion (Sharland et al. 2001). Due to intense denudation of the shield and resultant production of terrigenous material, sedimentation was almost completely siliciclastic-dominated, even up to several hundred kilometers from the edge of the shield.

In eastern Saudi Arabia the 300-m-thick Jauf Formation is composed of shallow-marine and eustarine sandstones (Rahmani et al. 2003), whereas to the northwest, including the Al-Jawf area, the succession is dominated by brackish, lagoonal, and shallow-marine shales, siltstones, and minor sandstones (Bahafzallah et al. 1981) (Fig. 1B). The northwestern province experienced periods of carbonate sedimentation. These limestone and dolostone horizons reflect periods of either maximum flooding or decline in siliciclastic input from the Arabian–Nubian Shield

(Bahafzallah et al. 1981; Al-Laboun and Walthall 1988; Al-Hajri et al. 1999; Sharland et al. 2001; Konert et al. 2001). These are the only carbonates preserved between the Middle Cambrian and uppermost Permian (Sharland et al. 2001), and they divide the otherwise monotonous shale-dominated Jauf Formation into five units (Sha'iba Shale, Qasr Limestone, Subbat Shale, Hammamiyat Limestone, Murayr Shale) that together represent two third-order transgressive–regressive pulses (Fig. 1C). The Sha'iba shales are interpreted to have formed in brackish environments (Bahafzallah et al. 1981) during the transgressive systems tract (TST) (Sharland et al. 2001), and the Qasr Member marks maximum flooding and the early highstand systems tract (HST). The appearance of fully marine conditions in the area studied near Al-Jawf is reflected by the development of microbial mounds and bryozoan–

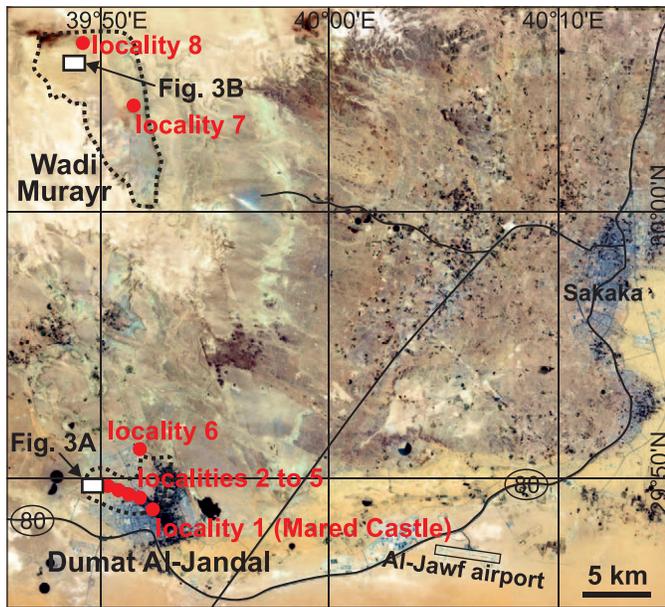


FIG. 2.—Satellite image of the Al-Jawf area, showing exhumed reefs (dotted areas) at the surface in Wadi Murayr and at Dumat Al-Jandal, and location of studied sections. Detailed satellite images of selected areas (white rectangles) are shown in Figure 3A, B. Source: google.com.

brachiopod limestones. In the Al-Huj and Ash-Shu'aybah regions, which are closer to the Arabian–Nubian Shield (Fig. 1B), stromatolites and gypsiferous shales formed in more restricted, peritidal settings (Al-Laboun and Walthall 1988). The Qasr Member is overlain by the gypsiferous Subbat shales, which represent hypersaline coastal plains and lagoons (Bahafzallah et al. 1981; Al-Laboun and Walthall 1988). These are considered to be late HST in the lower part and TST in the upper part (Sharland et al. 2001). They in turn are followed by alternating shales, limestones, and dolostones of the Hammamiyat Member, deposited in a marginal marine setting (Al-Laboun and Walthall 1988) during the early HST (Sharland et al. 2001). The sequence ends with the late HST deposits of the Murayr Member.

The Qasr reefs were first reported by Helal (1965), who mentioned “coralline lenses” and “coral mounds,” mainly in the lowermost 4 m of the Qasr Member, which largely consists of brachiopod-dominated limestones with occasional gastropods, pelecypod fragments, crinoids, and branched coral colonies (probably favositids). Bahafzallah et al. (1981) noted that the mounds are concentrated in two stratigraphic horizons; one (1.5 m thick) at the base of the Qasr Member, and the second (1 m thick) 4 m higher. These horizons are separated and overlain by 0.5–1.0 m thick units of brachiopod-rich and fine-grained carbonates. In the upper part of the member, gastropods, ostracods, and “globular inclusions which resemble *Sphaerocodium*” (oncoids) are locally common, though their structure is recrystallized. Chemical analysis (Bahafzallah et al. 1981) showed that, although the Qasr Member is usually described as limestone, pure limestone constitutes only ~ 8%, and the remainder is dolomitic limestone containing 17.6 to 20.3% MgO. Bahafzallah et al. (1981) inferred that the dolomitization was syndimentary, but the medium-crystalline microtexture with planar-e and planar-s fabric *sensu* Sibley and Greg (1987) is more characteristic of epigenetic dolomite. Al-Laboun and Walthall (1988) pointed out that the mounds locally laterally coalesce and directly overlie a widespread bed with abundant bryozoans and corals. They concluded that the mounds “indicate depths of normal sea water exceeding 5 meters” and grew on “gardens of bryozoans and corals” suggesting non-turbid conditions. The late Pragian–early Emsian

age of the Qasr Member is indicated by palynomorphs (Al-Hajri et al. 1999; Al-Ghazi 2007; Breuer et al. 2007) and by trilobite and conodont biostratigraphy (Boucot et al. 1989).

MATERIALS AND METHODS

The term “reef” is here used to indicate “essentially in place calcareous deposits created by sessile organisms” (Riding 2002). Reefs, inter-reefal facies, and their temporal–spatial relations on the platform are termed “reef complex.” The term “mound” is used to highlight the reef shape and should not be confused with “mud mound.” Other terminology used for description of microbialites follows Grey (1989), Braga et al. (1995), Riding (2000), and Shapiro and Awramik (2000).

Reefs and inter-reefal facies were examined at eight localities (see the Appendix, Localities). Seventy slabbed, polished samples were examined by binocular microscope, and 80 thin sections for microfacies analysis. Satellite images were used to determine spatial reef patterns. The erosion has removed the softer lithologies (marl, shale), resulting in excellent reef exposure, but consequently, observation of inter-reefal deposits is limited. A further limitation is that the Qasr Limestone Member has undergone pervasive dolomitization that has especially affected the reefs, but also—subordinately—the inter-reefal deposits. This recrystallization markedly limited microfacies description and interpretation. Nonetheless, since the recrystallization usually follows primary rock fabric, recognition of original components was possible in some cases. The development of small caves, typical of some of the reefs, was probably also associated with the dolomitization process.

REEFS AND INTER-REEFAL FACIES

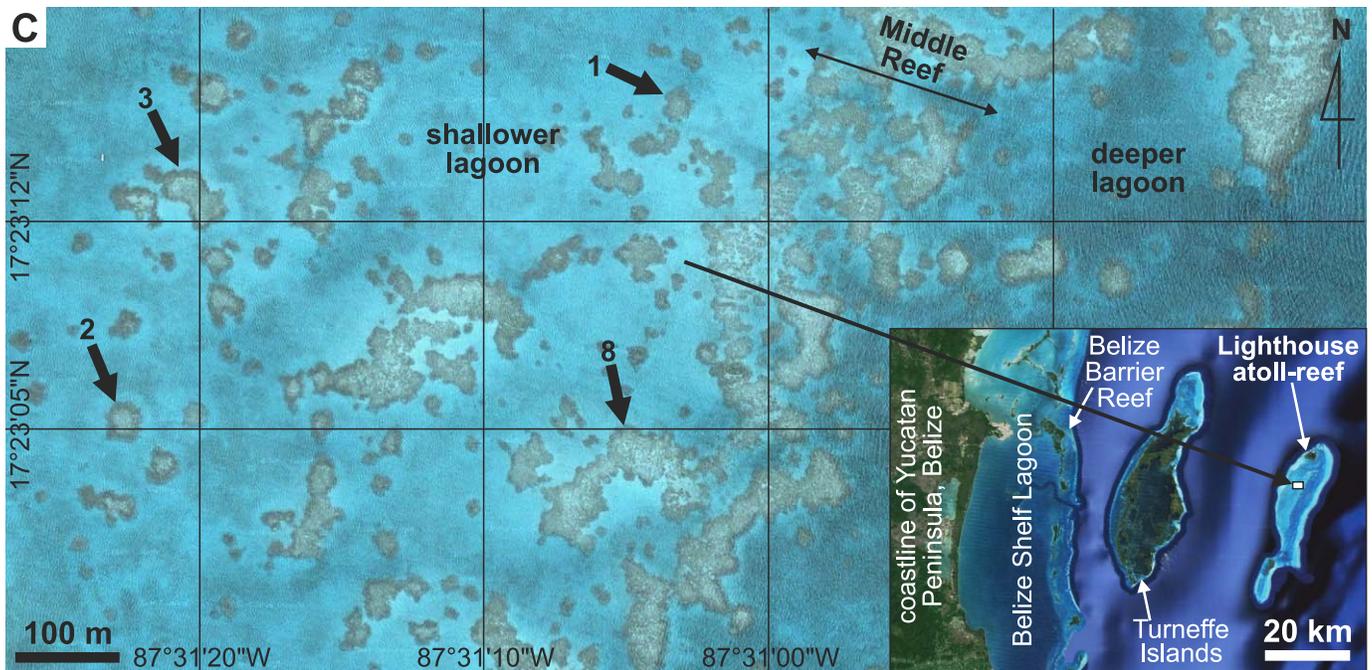
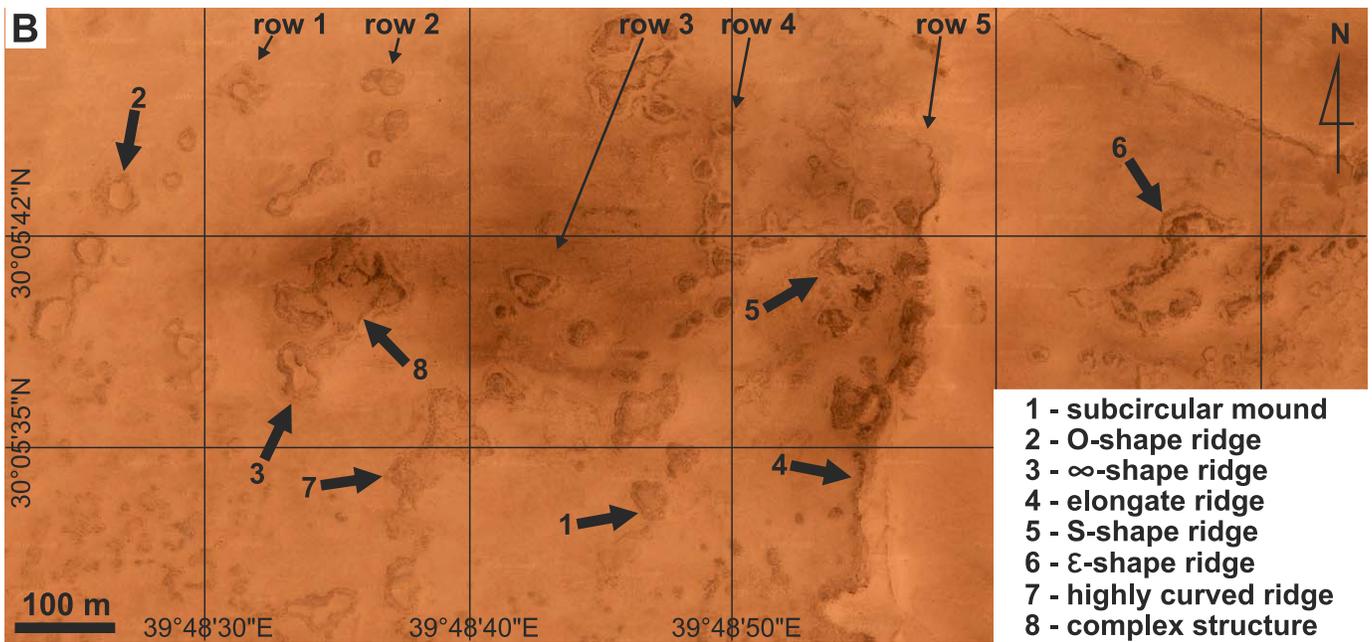
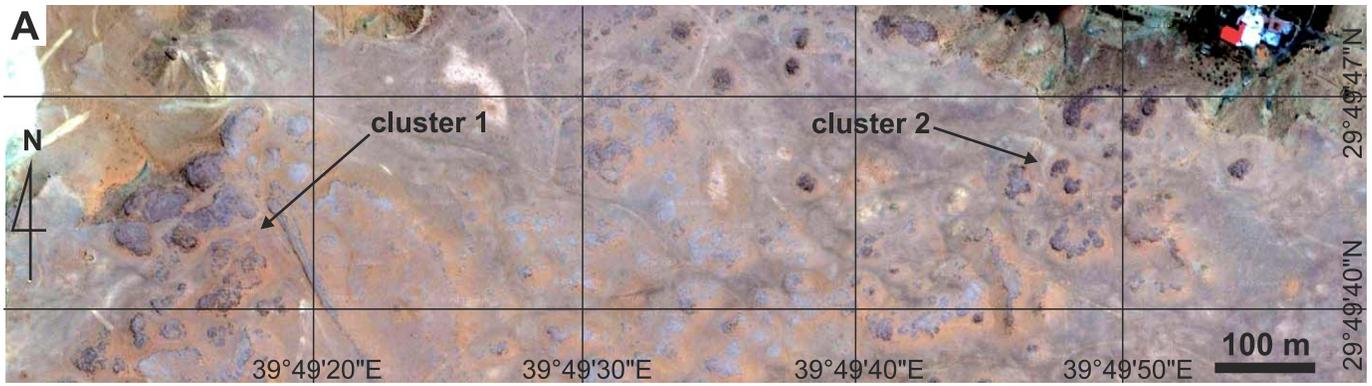
The Qasr reefs were studied in two adjacent areas: Wadi Murayr and near the town of Dumat Al-Jandal (Fig. 2) (see Appendix, Localities). The relative ages of individual reefal mounds within and between these areas often cannot be precisely estimated. However, since they all occur within the same ~20-m-thick interval (Qasr Member), we regard them as essentially contemporaneous.

Two main types of reef can be distinguished in these localities: microbial-dominated and metazoan-dominated. These differ markedly in internal composition and structure, external shape, and spatial arrangement.

Microbial-Dominated Reefs

Distribution and Morphology.—The microbial-dominated reefs are well developed in the vicinity of Dumat Al-Jandal, where both their upper surfaces and cross sections can be observed, together with the surrounding deposits. The reefs are circular to elliptical in plan and 1–15 m across. Their grouping shows crude NE–SW alignment (Fig. 3A). In cross section, the reefs are 1–6 m high and symmetrical. The reefs have distinct lens-like and knob-like cores, smoothly coated by external layers, whose arrangement determines the general shape of the reefs: bulbous and hemispheroidal reefs have oversteepened cortices, whereas mound and conical reefs have aggrading cortices (Figs. 4A, C, D, 5A, B, 6A, 7A, C). Mound and conical reefs are more common than bulbous and hemispheroidal reefs. The conical appearance of some reefs may also be a product of erosion.

Individual reefs locally grow upon each other, forming larger composite buildups of the same shape; bulbous and hemispheroidal reefs form high-relief steep-sided composite buildups 10 m high and 20 m across, whereas mound and conical reefs form low-relief mound-shape composite buildups 20–60 m across (Figs. 5A, B, 6A, 7C). Many reefs and composite buildups appear to be grouped into clusters, separated by areas in which reefs are sporadic or absent (Fig. 3A).



Composition.—The microbial-dominated reefs consist of cores and external layers. The cores do not exceed 1 m in height and 2 m in width, and in many cases are only decimetric in size (Fig. 4C). The outer layers can be up to 6 m in height, especially where the core is reduced in size (Fig. 5B). The cores are composed of centimeter-size greenish irregular mesoclots of dense microbial micrite, usually with aphanitic (leiolite) and occasionally laminated (stromatolite) fabric. Mesoclots are surrounded by gray-green-reddish allomicrite and microspar (Fig. 4E). Metazoan reef constructors have not been observed. The cores contain frequent dissolution vugs, which appear to have been formed during burial diagenesis (Fig. 4E). The external cortex is built by a series of centimeter- to decimeter thick microbialite layers. Each additional layer coats the preceding one, maintaining an approximately constant thickness around the core, except in the basal parts of bulbous reefs, where the cortical layers thin and finally disappear (Figs. 4D, 5B). Each cortical layer is composed of microbialite, which may be either columnar stromatolite, rind stromatolite, thrombolite, or leiolite (Fig. 8), although poor preservation often limits confident assessment of mesofabrics. Columnar stromatolites are composed of micrite, which also fills the space between columns. Some columns reach several decimeters in length and are better termed ridges. In cross section, individual columns are 1–5 cm wide and up to 30 cm high, and usually have ragged margins. In coarser-grained columns the convex-up lamination is more diffuse (Figs. 4F, 6D), and in finer-grained columns it is more crude (Figs. 6E, 7G). Columns can merge and then bifurcate (Fig. 6E). Smaller columns form very irregular dense nets, in which discrete columns are barely recognizable (Fig. 4F). Larger columns are readily visible because of their greater separation from neighboring columns (Fig. 6D, E). Columns can radially overgrow the underlying hemispherical surface, even on the sides of bulbous and hemispheroidal reefs, but some of the columns are then slightly curved upward, in the direction of the sea surface (Fig. 6E). It seems that the columnar stromatolites are more common within bulbous and hemispheroidal reefs, where columnar structure is also expressed on the surface as numerous wrinkles (Fig. 6C). In contrast, the upper surfaces of the columnar stromatolites within the mound and conical reefs is relatively smooth (Fig. 7B). Some layers of columnar stromatolites contain quartz grains trapped by the microbial surface (Fig. 7E). Rind stromatolites have distinct lamination, roughly parallel to the underlying semispherical surface, and the laminae are laterally discontinuous and wavy in form (Fig. 5C). Thrombolites are composed of distinct irregular mesoclots, which themselves display clotted internal structure. Mesoclots can constitute the whole rock volume or form botryoidal and somewhat dendritic clusters separated by micrite (Fig. 7F). Thrombolites appear to be more common within mound and conical reefs. Leiolites are generally structureless in mesofabric (Braga et al. 1995), although vague lamination visible in places suggests that these leiolites are related to the associated stromatolites.

Metazoan-Dominated Reefs

Distribution and Morphology.—Metazoan-dominated reefs are dominant in Wadi Murayr. Tens of them are well exposed, but their inter-reef facies are poorly exposed. In plan view, they range from subcircular

mounds 10–60 m across (typically 10–40 m), through curved and elongate ridges up to 300 m long, to more complex structures. Nonetheless, the orientation of their longer axes is roughly NNE–SSW (Fig. 3B). In cross section, the reefs are 2–4 m high, have gentle marginal slopes (up to several degrees), and do not show asymmetry (Fig. 9A). Many reefs are grouped into parallel rows, also running NNE–SSW. The distance between reefs within any one row does not exceed 50 m, and in some cases reefs are laterally linked. The distance between adjacent rows is ~ 100–150 m (Fig. 3B).

Composition.—Regardless of external shape, each metazoan-dominated reef is internally composed of lensoid and wedge-shaped units (Fig. 9C) that commonly overgrow each other in various directions to form a mosaic structure with shelter cavities. The framework of the units is formed predominantly by tube-shaped, spiral, and branched skeletons of unidentified metazoans. In many respects they resemble bryozoans, but poor preservation due to dolomitization prevents their confident recognition (Fig. 9D–F). The skeletons appear to have disorderly arrangement, which might be mainly due to mechanical destruction of original reef framework. Rare dendritic stromatoporoids (amphiporoids) occur in growth position. The space between skeletons is occupied by gray micrite and microspar that in some cases contain millimeter-scale areas of greenish irregular microbial crusts (Fig. 9E).

Shelter cavities between lensoid and wedge-shaped units are occupied by bedded bioclastic limestones (Fig. 9C) containing bryozoan(?) fragments (floatstone–rudstone). Some small knobs, situated on the reef sides, are overgrown by centimeter-thick columnar stromatolites (Fig. 9B).

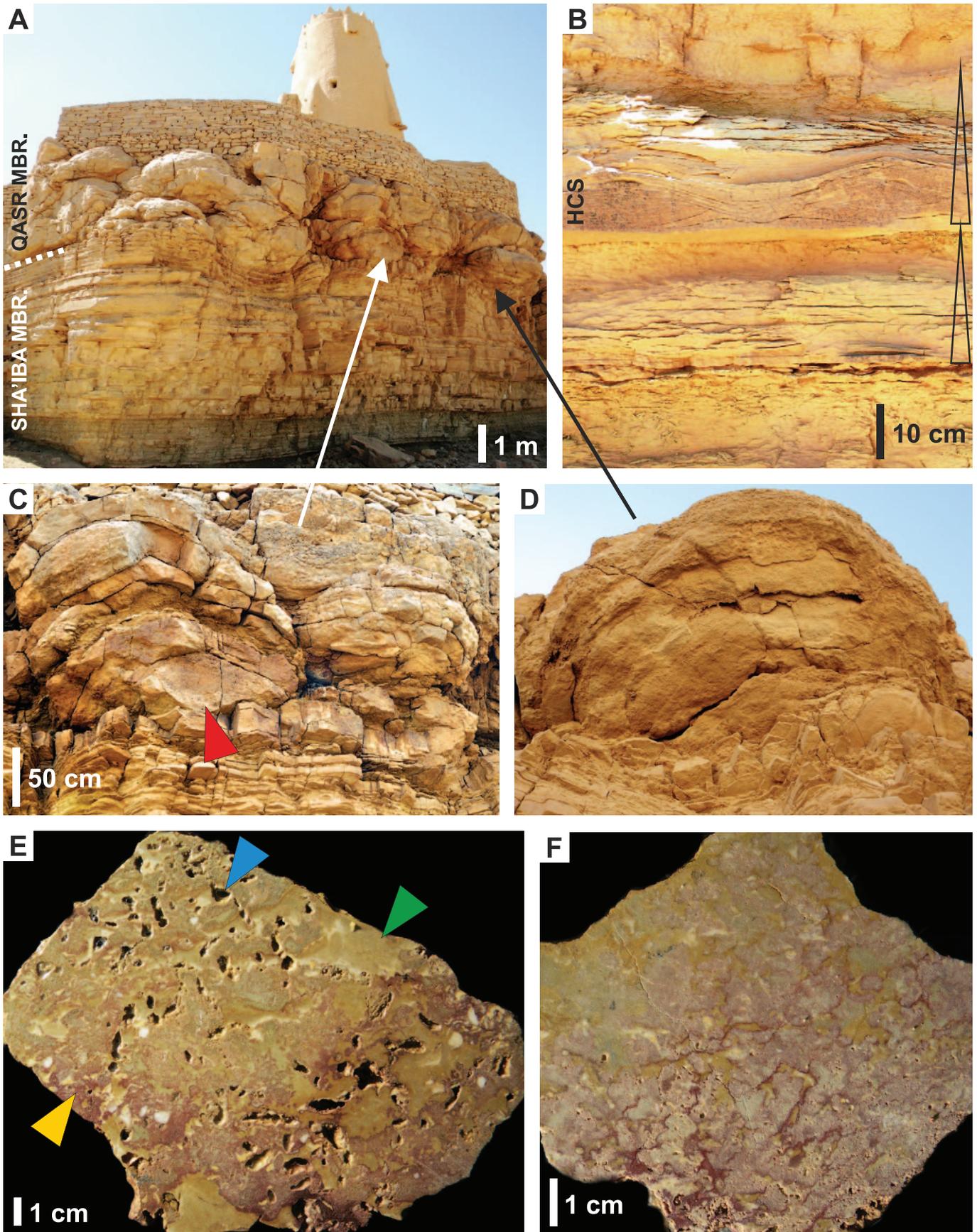
Underlying, Intervening, and Overlying Facies

The transition from the underlying Sha'iba Shale Member to the Qasr Member is well exposed at several localities. In general, both types of reef (microbial- and metazoan-dominated) rest on a 5-m-thick package of sandstone–siltstone couplets, which display typical tempestite features, such as sharp bases of erosional surfaces, normal grading, hummocky cross-stratification, and climbing-wave-ripple lamination (see Kreisa 1981; Duke 1985; Aigner 1985) (Fig. 4B). They are interpreted to represent lower-shoreface environments.

Loose samples probably of inter-reef carbonates include the following lithofacies: 1) laminated mudstone; 2) intraclast floatstone, containing angular lithoclasts of mudstone and rare fragments of bivalves, trilobites, algae, and ostracods (Fig. 10A, B); 3) bioclast floatstone, containing mixed brachiopod, bivalve, bryozoan, green algae, and crinoid fragments (Fig. 10C); 4) bioclastic floatstone–rudstone, with bryozoans, bivalves, and sporadic corals (Fig. 10D–F); 5) peloid grainstone with rare bivalves and green algae (Fig. 10G). The cliff section of the dry river valley 4.2 km north of Mared Castle shows that these carbonate lithofacies occur as intercalations within greenish marl and siltstone (lithologies not resistant to weathering, Fig. 5A). The association of low-energy muds and high-energy skeletal sands may represent occasional storm activity within an overall calm environment. Similar alternating lithologies 2 m thick directly overlie the reefs.

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FIG. 3.—Satellite images of Early Devonian and modern patch-reef patterns. **A**) Microbial-dominated reefs, well exposed near Dumat Al-Jandal, show subcircular shapes and crude NE–SW alignment and tend to be grouped into clusters. The reefs of cluster 1 are very closely spaced, whereas the spacing within cluster 2 is more open. **B**) Metazoan-dominated reefs, occurring in Wadi Murayr, form subcircular mounds up to 60 m across (arrow 1), closed ridges of O- and ∞-shapes up to 80 m across (arrows 2 and 3), elongate ridges up to 300 m long (arrow 4), open ridges of S-, ε- and sinusoidal shapes up to 200 m across (arrows 5, 6, 7), and complex structures 150 by 200 m in size (arrow 8). Regardless of their shape and size, most reefs are aligned in NNE–SSW parallel rows. **C**) Coralgal reefs in a modern Lighthouse atoll-reef lagoon, Belize, form variform patches, including subcircular mounds (arrow 1), O- and ∞-shape ridges (arrows 2 and 3), and more complex structures (arrow 8). Despite tectonic segmentation of the platform interior into deeper and shallower lagoons separated by Middle Reef, most patches follow the general NNE–SSW orientation of these structures and the atoll margin, which is approximately perpendicular to the mean wave and storm approach from the east. Source: google.com.



The transition from the Qasr Member to the overlying Subbat Shale Member was not observed in the sections. The Subbat Member commences with variegated mudstones with chicken-wire anhydrite, indicative of arid lagoonal–supratidal environments (Bahafzallah et al. 1981).

DISCUSSION

The Qasr reefs have recrystallized microfabrics and at best only poorly preserved mesofabric, which hinder assessment of controls on reef development and demise, especially at the “micro” level. Nevertheless, information about the sedimentary environment is provided by the size and shape of the entire reef and its components, as well as from the associated, less altered bedded deposits.

Paleoenvironmental Conditions

Microbial buildup microstructure is determined largely by the activity and composition of microbial communities, with less influence from the physical environment (Gebelein 1976; Ginsburg 1991; Andres and Reid 2006). Microbes regulate precipitation and lithification, and are responsible for passive grain trapping (Chafetz and Buczynski 1992; Visscher et al. 1998; Macintyre et al. 2000; Reid et al. 2000; Riding 2000, 2011). In contrast, microbialite morphogenesis strongly reflects physical environmental factors, such as accommodation space, sediment supply, and/or hydrodynamics (Logan et al. 1964; Hoffman 1976; Kennard 1994; Pratt and James 1982; Braga et al. 1995; Feldmann and McKenzie 1997; Andres and Reid 2006; Jahner and Collins 2012). The microbial-dominated reefs of the Qasr Member are 1–6 m high and are internally built of several continuous microbialite layers. The persistence of microbialite layers around the entire growth surface indicates that, while growing, the individual reefs possessed relief of several meters above the seafloor and that their sides were not covered by sediment. This relief indicates accommodation space of at least several meters and that the reefs accreted during periods when rate of reef aggradation was greater than rate of inter-reef sediment accumulation. These observations support the conclusion of Al-Laboun and Walthall (1988) that Qasr reefs generally grew in water depths exceeding 5 m. The microbialites display overall fine-grained mesotextures lacking constructional voids, suggesting that the microbial mats were covered exclusively by fine particles. The various types of microbialite and their morphological forms indicate temporal variation in paleoenvironment during reef accretion. Decreased accumulation rates enabled lateral expansion of microbial mats over the reef surface, which resulted in the formation of planar forms (rind stromatolites) (cf. Dupraz et al. 2006). Increased rates of mud accumulation could have led to the formation of high-relief forms (columnar stromatolites) with ragged margins. The cause of branching and merging of columns remains unclear. Hofmann (1969) suggested that branching occurs when unbound detritus accumulates on a microbial mat and interrupts uniform column growth. Pratt and James (1982) inferred that anastomosing branches occur when microbial mats expand laterally and colonize areas between columns. Some columnar stromatolites, overgrowing the sides of bulbous and hemispheroidal reefs, have upward-curved columns, which might reflect the capacity of cyanobacteria to optimize photosynthesis rates by vertical phototactic movement (e.g., Black 1933; Monty 1976; Foster et al. 2009), suggesting that the stromatolitic microbial communities were dominated by autotrophs.

Thrombolites within the Qasr microbial-dominated reefs are more difficult to interpret because the origins of mesofabric and the paleoenvironmental significance of thrombolites are generally poorly understood (Riding 2011). Kennard and James (1986) proposed that clotted fabric is primary in origin and produced when the microbial community is dominated by coccooid microbes. Walter and Heys (1985) suggested that thrombolites may be stromatolites whose original laminated fabric was disturbed and modified by bioturbation or diagenesis. Braga et al. (1995) regard thrombolitic fabric as resulting from irregular and uneven supply of poorly sorted sediment onto patchily distributed microbes. The origins of the Qasr thrombolites are not obvious. No macrofossils and ichnofossils were found within the fabric.

The metazoan-dominated Qasr reefs are 2–4 m high and display an internal mosaic structure composed of overgrown lenticular and wedge-shaped units, and shelter cavities. This internal pattern suggests that the reef growth was uneven and patchy, and that the final buildup originated from the lateral accretion and merging of smaller dispersed patches. The reef framework is formed by tube-shaped, spiral, and branched metazoan skeletons that are surrounded by fine-grained matrix with thin microbial impregnations. Poor preservation hinders assessment of whether the abundant skeletal elements belong to bryozoans, although their size and the arrangement of septa are consistent with a bryozoan affinity. Moreover, bryozoan fragments occur in the less altered, bedded deposits adjacent to the reefs and have also been reported by previous authors (Al-Laboun and Walthall 1988). Irrespective of their affinities, these tubiform, spiral, and branched metazoan organisms appear to have baffled suspended fine particles, as indicated by micrite between their skeletons, contributing to the development of these reef structures and ongoing generation of positive topographic relief.

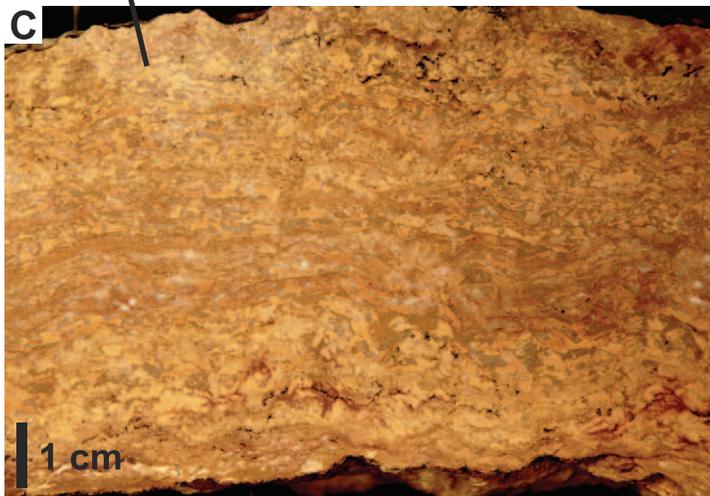
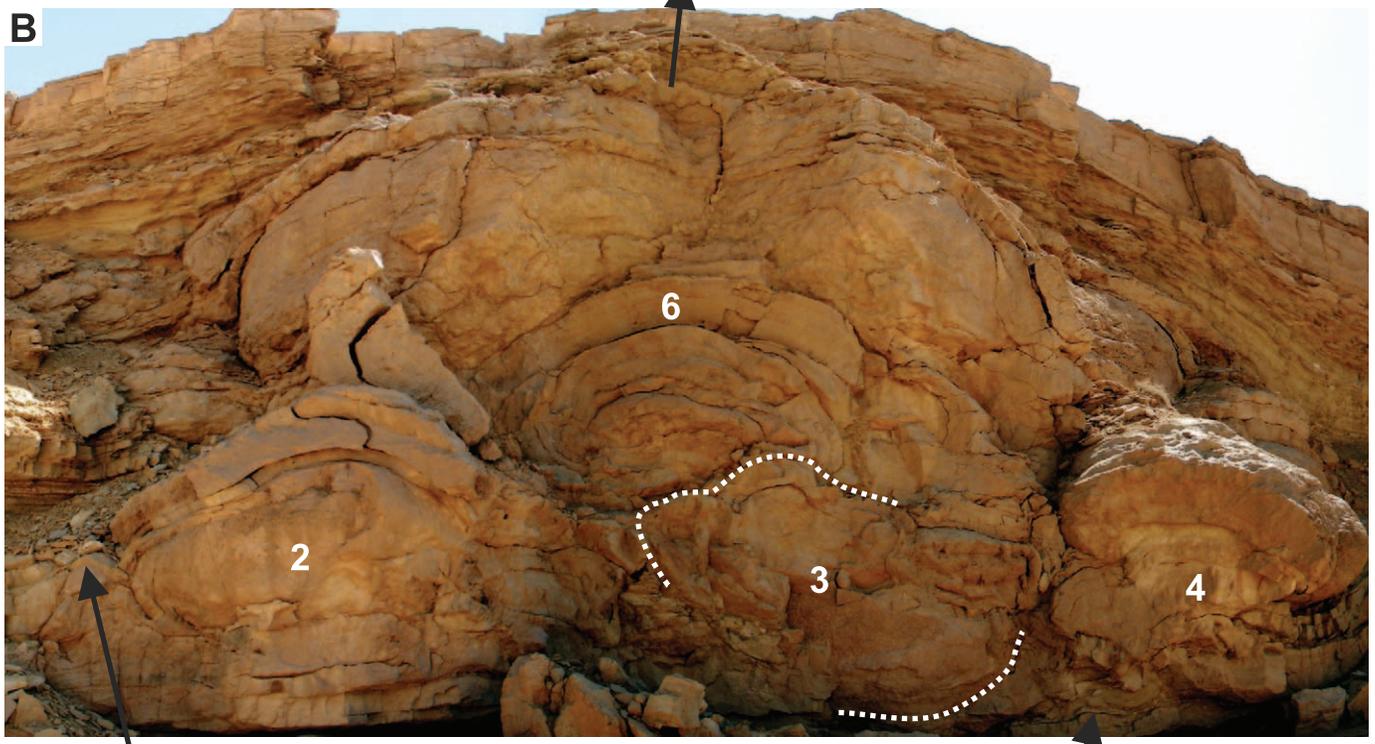
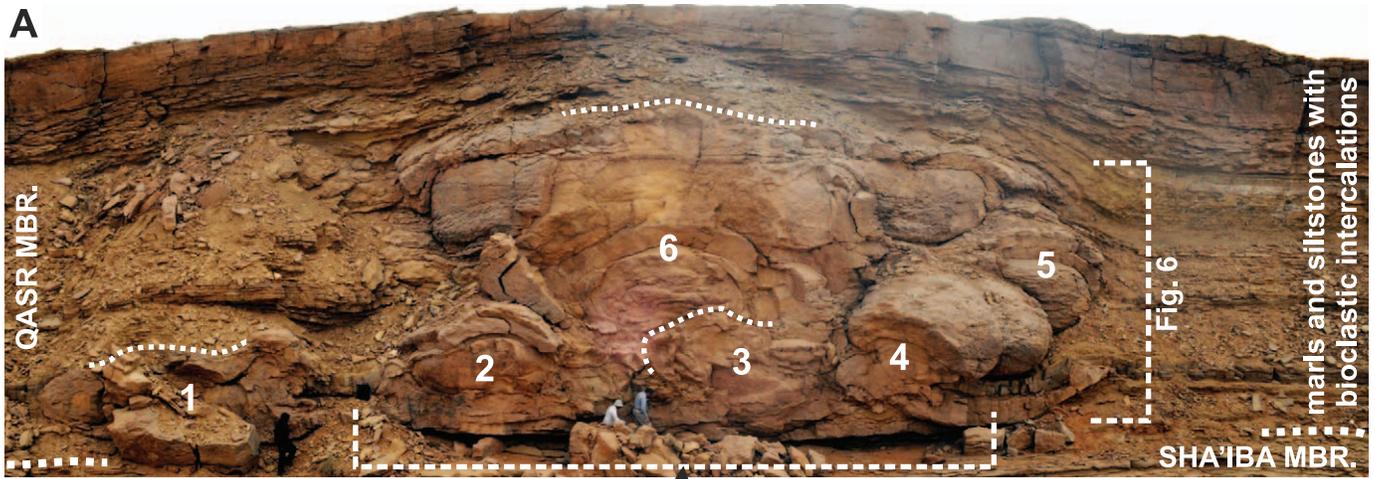
Both microbial- and metazoan-dominated reefs of the Qasr Member are enclosed and separated by bedded deposits; mainly thick packages of marl, siltstone and mudstone, which suggest that much of the sedimentation occurred in low-energy conditions. On the other hand, bioclast and intraclast intercalations within the fine-grained, bedded sediment must have been deposited by recurring high-energy events, such as storms. Such a variable energy regime is typical of depth zones between normal wave base and storm wave base (e.g., Aigner 1985). This interpretation is strengthened by the fact that the Qasr reefs directly overlie the sandstone–siltstone tempestites of the Sha’iba Member. It is unlikely that the bioclastic–intraclastic material was delivered from outside the Qasr reef complex, because most bioclasts are unbroken (though disarticulated) and the lithoclasts are angular, which suggests short transport. Moreover, no skeletal fragments (except the frame builders) were found in either the metazoan- or microbial-dominated reefs, indicating that the reef surface was not inhabited by skeletal organisms and thus that the reefs themselves were not a source of bioclasts. Presumably, the inter-reefal areas were colonized by bryozoans, brachiopods, bivalves, green algae, and crinoids, whose skeletons were subsequently reworked by currents. This stenohaline biota indicates normal marine salinity, at least periodically.

Paleogeography of the Qasr Reef Complex

Whereas plan views of orientation and arrangement are readily observed in modern reefs, ancient reefs are most commonly seen in subvertical sections that reveal their cross-section shape more than spatial

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FIG. 4.—Microbial-dominated reef, Dumat Al-Jandal (all except B are Locality 1). **A**) Several bulbous and hemispheroidal reefs, stacked upon each other and directly overlying a 5 m tempestite unit of the upper Sha’iba Member. **B**) Two tempestites displaying normal grading (open triangles) and hummocky cross-stratification (HCS) in the upper sandstone layer (Locality 4). **C**) Cross section of hemispheroidal reef with lenticular vuggy core (red arrow). **D**) View upward to base of bulbous reef; note oversteepened microbial cortex. **E**) Vertically oriented slab of reef core composed of micrite (yellow arrow) and mesoclots of dense microbial micrite (green arrow); blue arrow indicates dissolution vug, cutting both mesoclot and micrite. **F**) Vertically oriented slab of cortex layer formed by columnar-digitate stromatolite.



pattern. There are some remarkable Devonian exceptions to this: e.g., Middle Devonian carbonate mud mounds (Wendt et al. 1997) and reefs (Dumestre and Illing 1967; Wendt and Kaufmann 2006) in the northwestern Sahara, and parts of the mid–Late Devonian Canning Basin barrier reef complex in Western Australia (Playford et al. 2009). The Qasr Member outcrops described here provide unique examples of well-exposed Early Devonian patch reefs in plan view, showing reef distribution, alignment, and orientation over areas of up to 1 km² (Fig. 3A, B). Both the microbial and metazoan Qasr reefs formed as distinct ridges, mounds, and domes on the platform. The metazoan-dominated reefs in Wadi Murayr are clearly NNE–SSW-oriented and grouped into NNE–SSW-oriented parallel rows. The microbial-dominated reefs in the Dumat Al-Jandal vicinity exhibit NW–SE orientation, although this is less obvious (Fig. 3A, B). These distributions suggest regional controls over reef orientations.

Modern patch-reef complexes are widespread in shallow tropical carbonate environments, e.g., Great Barrier Reef in Australia (Hopley et al. 2007), Fiji (Ferry et al. 1997), and Bermuda (Garrett et al. 1971). Other well-studied examples are three isolated platforms of offshore Belize: Lighthouse, Glover, and Banco Chinchorro platforms (Gischler 1994, 2003; Gischler and Hudson 1998; Gischler and Lomando 1999). Lighthouse atoll-reef contains patch reefs of similar size range (mostly up to 60 m across) and density of occurrence (distance between reefs up to 150 m) as Qasr reefs, as well as local unidirectional alignment and grouping into rows (Fig. 3C). Lighthouse patch-reef complex is situated on an elongate, isolated, fault-bounded platform, ca. 35 km by 7.5 km in size, oriented parallel to the Yucatan Peninsula (Fig. 3C). The platform is rimmed by a coral–red–algae–*Halimeda* reef, especially on the eastern windward margin, where it is accompanied by a distinct sand apron (Gischler 1994). The well-circulated lagoon is floored by carbonate sediments and hundreds of variform coralline patch reefs (Fig. 3C), whose compositions are determined by variations in the energy regime (Gischler 1994; Gischler and Lomando 1999). The 3-m-deep western lagoon is floored by peloidal–skeletal wackestone–grainstone and *Montastraea annularis*-dominated patch reefs, whereas the 8-m-deep eastern lagoon has mollusk–foraminifer–*Halimeda* wackestone–packstone enclosing *Acropora palmata*-dominated patch reefs. These two lagoonal areas are separated by a long ridge (Middle Reef) composed of coalescing *Montastraea annularis*-dominated patch reefs and skeletal grainstone. The shallower and deeper lagoon, as well as Middle Reef, are aligned parallel to each other and to the long axis of the platform. This trend is also followed by most of the patch reefs scattered over the entire platform (Gischler and Hudson 1998).

The facies patterns on the Lighthouse platform are controlled by both antecedent (tectonic and karst) topography and degree of exposure to waves and currents (Gischler and Lomando 1999). Deeper and shallower lagoons were established respectively on the footwall and hanging wall of a pre-Holocene fault that cuts the basement lengthwise, whereas the margin reef and Middle Reef developed on topographic highs of Pleistocene limestones (Gischler and Hudson 1998; Gischler 2003). On the other hand, the asymmetric facies distribution, including the wide continuous reef and sand apron of the eastern platform margin and the narrow patchy reef development on the western margin, results from the easterly waves and storms (Gischler and Hudson 1998). The area is in the Trade Wind belt; as a result the mean wave approach is from the NEE (approx. from 75°) and most storms come from the east (Gischler and Hudson 1998; Gischler 2003).

The similarities in spatial arrangement between the Lighthouse and Qasr patch reefs suggest similar influences on reef development. However, without more detailed investigations (especially subcrop data), the question remains open to what degree paleotopography and patterns of water movement dictated the architecture of the Qasr reef complex.

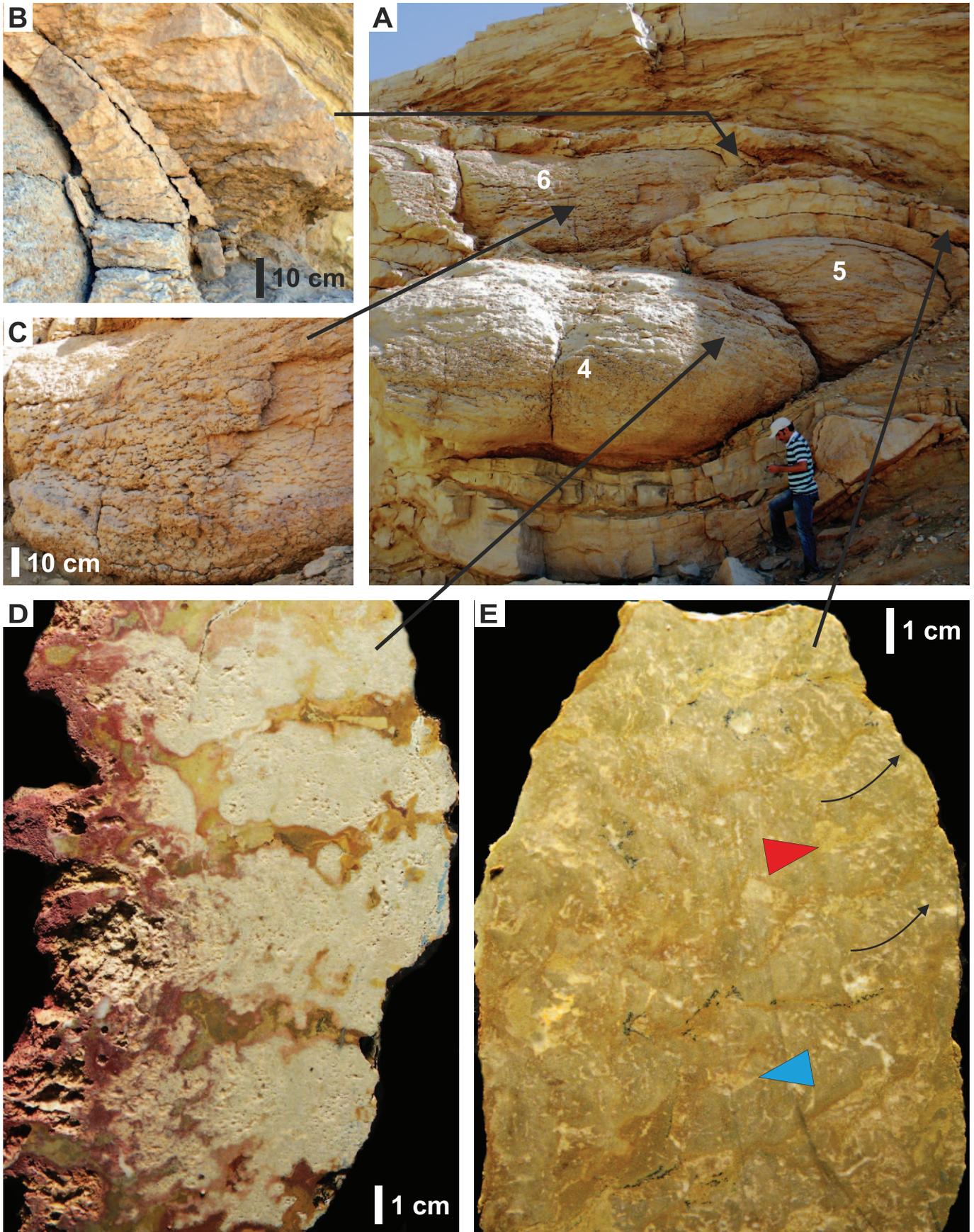
Late Silurian–Early Devonian Reef “Crisis”

Fagerstrom (1987) drew attention to Late Silurian–Early Devonian decline in the size and number of reefs and in stromatoporoid species diversity. The Qasr reefs developed towards the end of this “extended reef crisis” (Flügel and Kiessling 2002). During this period of 10–15 My, reefs were less abundant, smaller (Flügel and Flügel-Kahler 1992; Copper 2002; Kiessling 2002), and commonly dominated by stromatolites or other microbial carbonates (Clough and Blodgett 1989; Soja 1991, 1994; Kiessling 2002). Many earliest Devonian coral–stromatoporoid reefs are thin biostromes (e.g., Fernández-Martínez et al. 2010), but there are also Late Silurian–Early Devonian reef complexes up to hundreds of meters thick composed mainly of either stromatoporoids (Bourque et al. 2001) or stromatolites (Clough and Blodgett 1989; Antoshkina 1998; Antoshkina and Königshof 2008). Encrusting calcimicrobes can be important components, in addition to sponge and coral skeletons (Wolf 1965; Adachi and Ezaki 2007). Stromatolites are prominent in Late Silurian reefs of SE Alaska (Soja 1994) and are important components of upper Lochkovian reefs in the Polar Urals that are up to 170 m thick (Antoshkina and Königshof 2008), and of Pridoli–Pragian reefs in SW Alaska that are up to 500 m thick (Clough and Blodgett 1989). These are reconstructed to be equatorial deposits (Copper 2002). Much farther south, other reefs of approximately this age thought to be of latitude similar to that of Al-Jawf include thick (up to 600 m) Late Silurian–Early Devonian coral–bryozoan–stromatoporoid reefs (Bourque and Amyot 1989; Bourque et al. 2001) and carbonate mud mounds (Bourque and Raymond 1989) in Gaspé, Quebec, Emsian tabulate–stromatoporoid reefs in the Cantabrian Mountains, Spain (Méndez-Bedia and Soto 1984; Méndez-Bedia et al. 1994; Rodríguez et al. 2010), and thin Lochkovian stromatoporoid–tabulate reefs in New York (Isaacson and Curran 1981; Stock 1997). These studies indicate considerable variety of small to large stromatolite and metazoan reefs during the Late Silurian to early Emsian (10–15 My) interval. Nonetheless, global syntheses have consistently concluded that reefs during this interval were less abundant and smaller, with lower skeletal diversity and fewer stromatoporoids, than those before and afterwards (Flügel and Flügel-Kahler 1992; Copper 2002; Kiessling 2002). They were also commonly dominated by stromatolites or other microbial carbonates (Clough and Blodgett 1989; Soja 1991, 1994; Kiessling 2002), but at the same time they were also associated with normal marine metazoans (Soja 1991, 1994; Soja et al. 2000, 2003). Despite poorer fabric preservation, Qasr reefs also support this microbial–metazoan marine association.

The concept of stromatolite and related microbialite resurgence in the aftermaths of mass extinctions (Schubert and Bottjer 1992) is a corollary of the view that, if metazoans can competitively exclude microbial carbonates (Fischer 1965; Garrett 1970; Awramik 1971), then temporary reduction in metazoan abundance and diversity in the aftermaths of mass extinctions should permit temporary increase in microbial carbonates. This “disaster biota” effect has been widely invoked to account for microbialite development following end-Permian extinctions (Schubert and Bottjer 1992, 1995), and might also apply to Late Devonian extinctions (Riding 2006). Decline in skeletal reef biotas could have

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FIG. 5.—Microbial-dominated reef, Locality 6, northern outskirts of Dumat Al-Jandal. **A**) Six stacked bulbous and hemispheroidal reefs, forming high-relief steep-sided composite buildup surrounded by detrital bedded deposits. **B**) Close view of Part A; note oversteepened microbial cortex up to 6 m high in reef number 6. **C**) Vertically oriented slab of rind stromatolite with disturbed discontinuous lamination. **D**) Greenish marl (red arrow), filling shelter cavity between two reefs.



contributed to the development of microbialite reefs, such as those in the Qasr Member. A relatively short-lived resurgence of microbialites and “anachronistic facies” within the Late Silurian has been connected to brachiopod and conodont (but not reef) extinctions (Calner 2005). However, the Qasr reef complex is relatively large and the reefs are composed of a combination of microbialite-dominated and metazoan-dominated buildups and inter-reef deposits (though limited in preservation) that contain abundant stenohaline metazoans. This is inconsistent with the “disaster biota” hypothesis. Only if there were little or no metazoans in the reef complex would the argument be supported; this is clearly not the case. Similar arguments can be marshalled for Late Silurian Uralian Seaway reefs. Soja (1991) showed that Late Silurian stromatolite-dominated shelf-edge reefs in SE Alaska formed under normal marine conditions in high-energy environments by microbes that “prevailed in the presence of frame-building skeletal metazoans.” It has consequently been argued that large subtidal stromatolite reefs along the margins of the Uralian Seaway challenge “the notion that Phanerozoic stromatolites largely were restricted to intertidal environments or only rose to dominance in the wake of mass extinctions in the marine realm” (Soja et al. 2000).

Soja et al. (2004) emphasized that the sedimentological importance of microbial carbonates endured in many reefs throughout the Phanerozoic. Based on Late Silurian reefs along the margins of the Uralian Seaway (Alaska, Ural Mountains, and the Salair region) to which stromatolites, sphinctozoan sponges, and hydroids all contributed, they argued that the microbial components could have been favored by increase in terrestrial nutrient runoff as well as by “relaxed ecological landscapes after the regional decline of metazoan competitors.” In addition, factors that stressed metazoans may simultaneously have promoted microbial development. Although reasons for Late Silurian until the early Emsian “extended reef crisis” remain uncertain, global changes at this time include sea-level fall (Vail et al. 1977; Haq and Al-Qahtani 2005), which reduced the extent of shallow seas (Sloss 1963; Ronov 1994) and reefs (Copper 2002) and increased siliciclastic supply, which reduced carbonate platform development (Stanley 2001). In addition, oxygen-isotope data indicate unusually high temperatures persisting into the Emsian (Joachimski et al. 2009). Qasr reefs developed during an episode of maximum transgression within one of several third-order transgressive-regressive pulses that affected the broad shelf region northeast of the Arabian–Nubian Shield (Haq and Qahtani 2005). As a result of denudation of the shield, siliciclastic sediment dominates the Late Cambrian to latest Permian succession of this region. The only sequences containing carbonate horizons are in the Early Devonian Jauf Formation (Sharland et al. 2001), which represents the episode of global warming identified by Joachimski et al. (2009). As noted for the Late Devonian, elevated sea-surface temperatures could have limited growth of coral-stromatoporoid reefs while at the same time favoring microbial growth and calcification (Joachimski et al. 2009).

This approach underscores the contention of Soja et al. (2004) that reefs near the Silurian–Devonian transition require a nuanced explanation for the presence of coeval well-developed stromatolite reefs with associated metazoan biotas. In Qasr examples the metazoans are most conspicuous in inter-reef facies, whereas in the better-preserved Uralian Seaway reef sponges commonly occur within the stromatolite reefs (Soja 1991; Soja and Antoshkina 1997). We propose that factors that conspired to reduce development of metazoan reefs at this time, encouraged

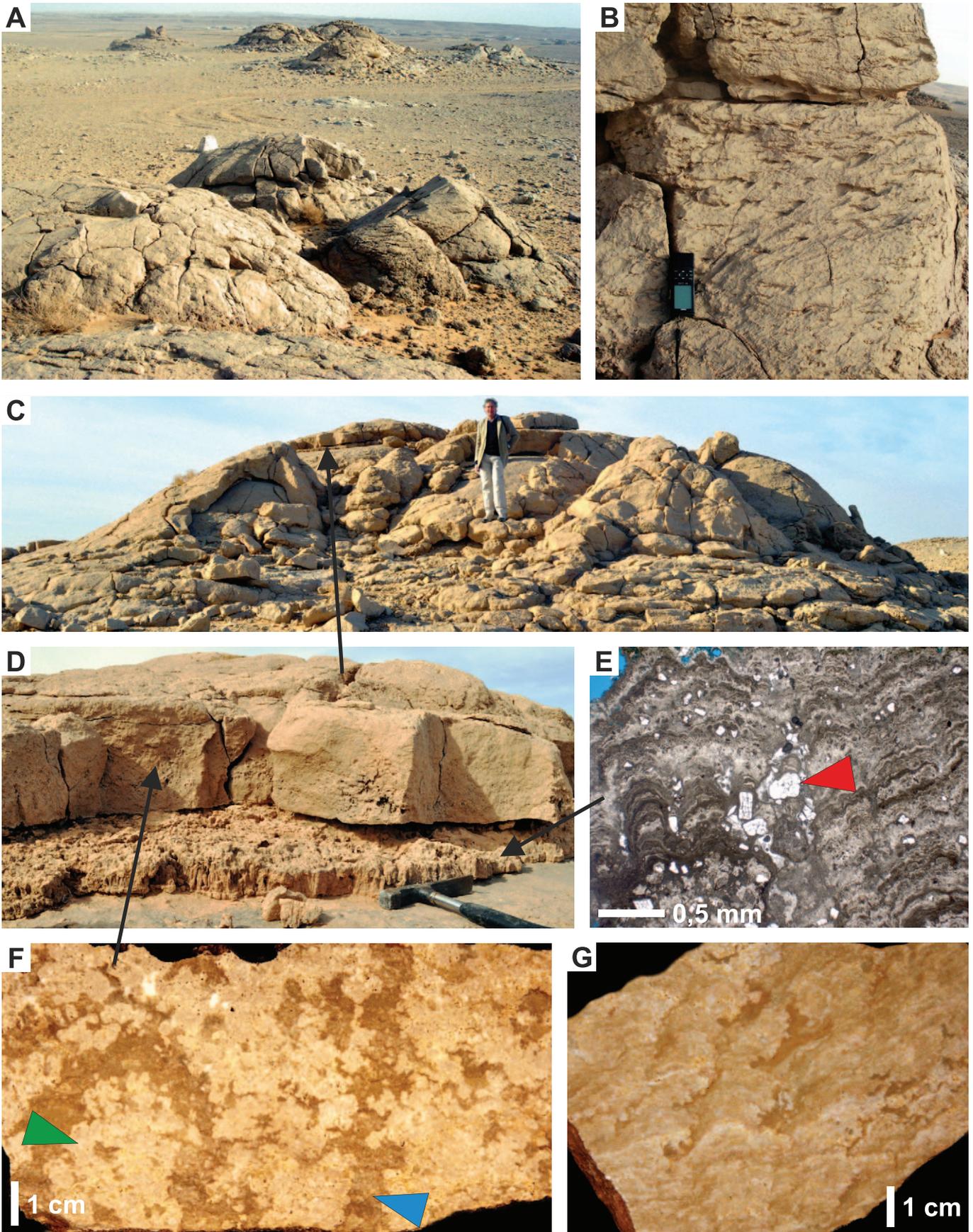
development of microbial carbonates, producing large stromatolite-dominated reefs in normal marine subtidal environments in which metazoans also locally thrived. These factors could have included increased coastal nutrient supply and relatively elevated temperatures.

CONCLUSIONS

1. The late Pragian–early Emsian Qasr complex consists of numerous decametric patch reefs that developed in generally low-energy environments in turbid to clear waters. The reefs are extensively dolomitized but are separated by bioclastic limestones and by carbonate and siliciclastic muds. Interreef biotas include stenohaline marine bryozoans, brachiopods, bivalves, crinoids, and green algae that were reworked to produce the bioclastic limestones. Both microbial- and also metazoan-dominated reefs can be distinguished within the 20-m-thick Qasr Member.
2. The microbial-dominated reefs are circular to elliptical thickly layered mounds and domes, up to 6 m in height and 15 m across, that commonly coalesce into composite bioherms. Dolomitization hinders fabric recognition, but stromatolite, thrombolite, and to a lesser extent leiolite macrofabrics are discernible. These microbial carbonates appear to lack constructional voids and macrofossils. Fluctuations in accumulation rate most likely produced morphologic variations of stromatolites, from planar (rind stromatolites) representing reduced supply of carbonate mud, to high-relief forms (columnar stromatolites) under increased mud deposition. The origin of thrombolitic fabric is unclear. The leiolites, locally displaying vague lamination, seem to be related to the stromatolites.
3. The metazoan-dominated reefs form subcircular mounds 10–60 m across, curved and elongate ridges up to 300 m long, and more complex structures that appear to be aligned approximately perpendicular to wave action. Dolomitization hinders skeleton identification. The reefs appear to be composed of poorly preserved tube-shaped, spiral, and branched fragments, possibly bryozoans, in fine-grained matrices. These reefs possibly accumulated as a result of baffling of lime mud by bryozoans.
4. Although their microfabrics are commonly dolomitized, the external features of these abundant Qasr patch reefs, including size, morphology, and spatial distribution, are exceptionally well displayed by extensive desert outcrops of the original carbonate platform surface. These patterns closely resemble those of some modern coralgall patch reefs (e.g., Belize), demonstrating that, irrespective of major differences in composition and age, marine patch reefs on shallow carbonate platforms can develop strikingly similar sizes, shapes, and arrangements, suggesting common intrinsic responses to environmental controls on reef growth.
5. Qasr reefs, despite being limited by poor internal fabric preservation, provide striking outcrop examples of Early Devonian microbial reefs that support earlier studies that recognize large-scale microbial reefs associated with diverse metazoan biotas. This association remains incompletely understood. It suggests factors that promoted widespread microbial growth in normal marine subtidal environments where skeletal reef builders were scarce and/or inhibited. This could have included decline in skeletal reef builders capable of colonizing rapidly accreting stromatolites. The

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FIG. 6.—External microbial layers of selected reefs; same locality as Figure 5. **A)** Close view of Figure 5A showing amalgamation of reefs number 4 and 5; note wrinkled upper surface of cortical layers. **B)** Detail of three cortex layers built by radially growing columnar stromatolites. **C)** Wrinkles on upper surface of columnar stromatolites. **D)** Vertically oriented slab of coarser-grained columnar stromatolite with diffuse lamination; the right side is outward. **E)** Vertically oriented slab of finer-grained columnar-branching stromatolite with crude lamination; the right side is outward. Some columns merge (blue arrow) while others bifurcate (red arrow). All columns are slightly upward curved (black arrows).



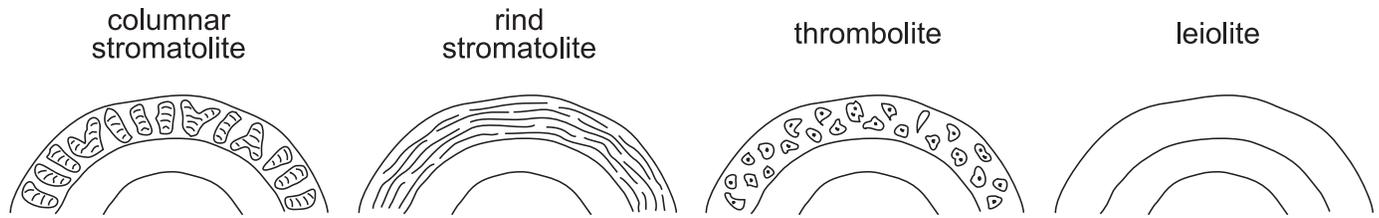


FIG. 8.—Generalized types of Qasr reef microbialite cortex layers. Not to scale.

growth of microbial mounds in apparently shallow-water, normal-marine salinity environments suggests that they were able either to outcompete and/or inhibit other reef builders. Further studies are required, including detailed documentation of reef composition and community diversity, to help distinguish extinction patterns, sea-level change, temperature, and other effects that determined the development of Late Silurian–Early Devonian reefs.

ACKNOWLEDGMENTS

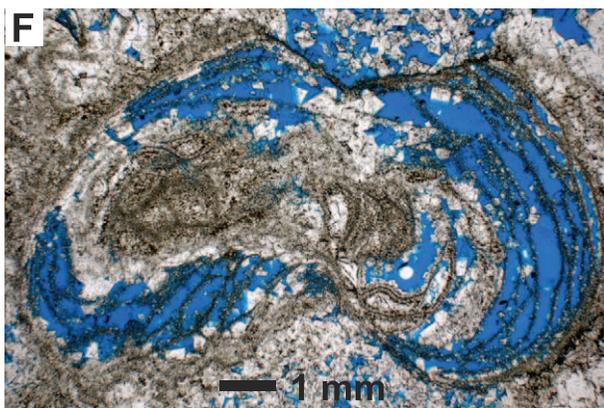
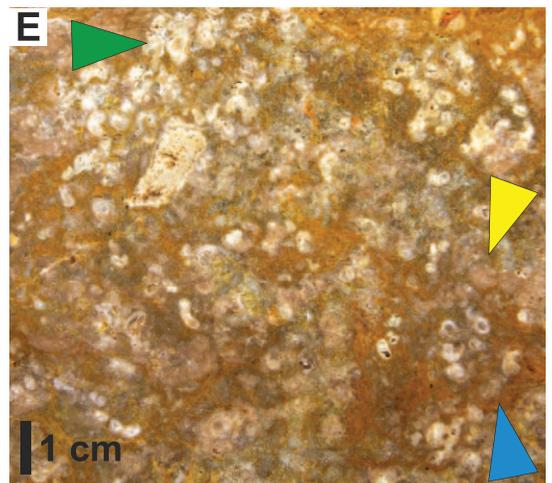
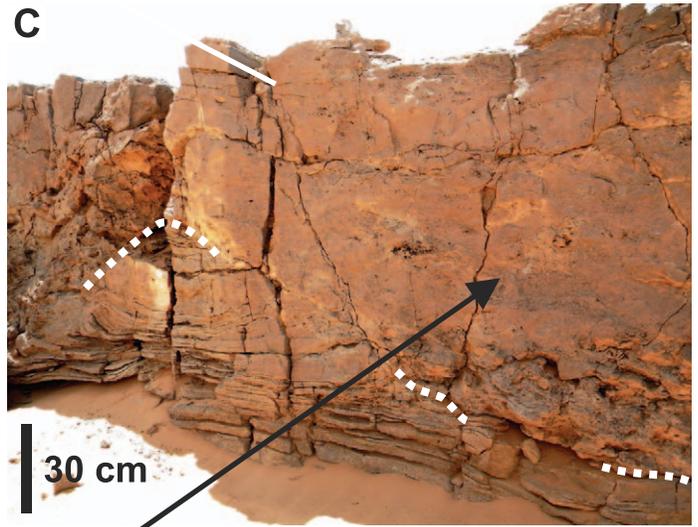
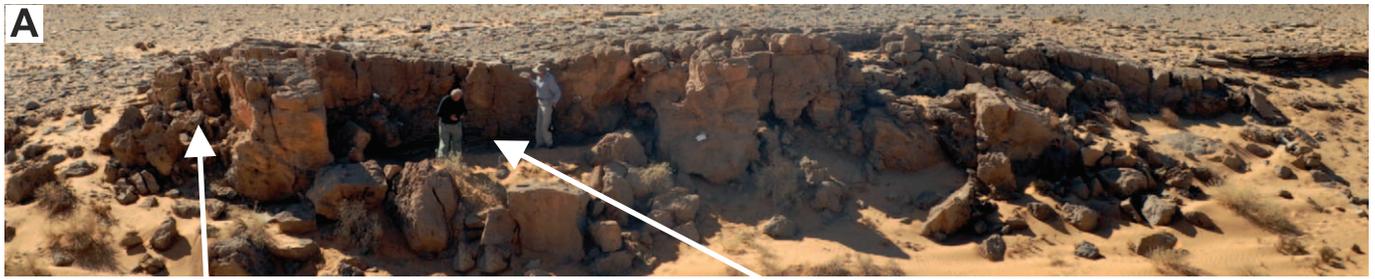
Grant # IN101023 from King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia, supported this research. We are grateful to Muhittin Senalp for his guidance and help in the field. The final manuscript benefited considerably from the suggestions of editors Maya Elrick and Gene Rankey, reviewer Dan Lehrmann, and an anonymous reviewer.

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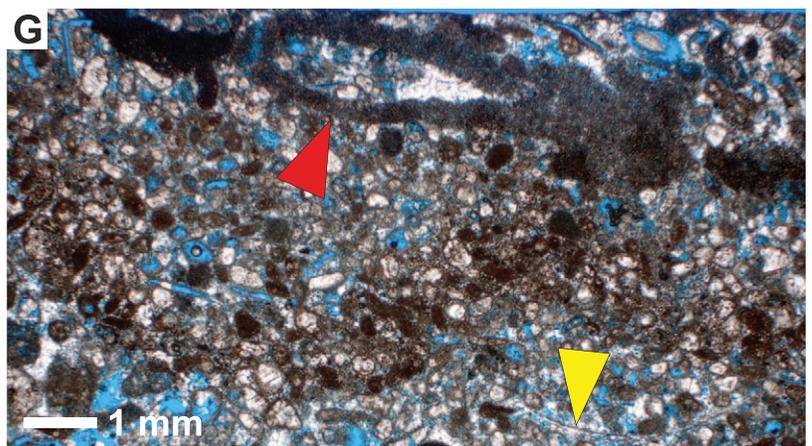
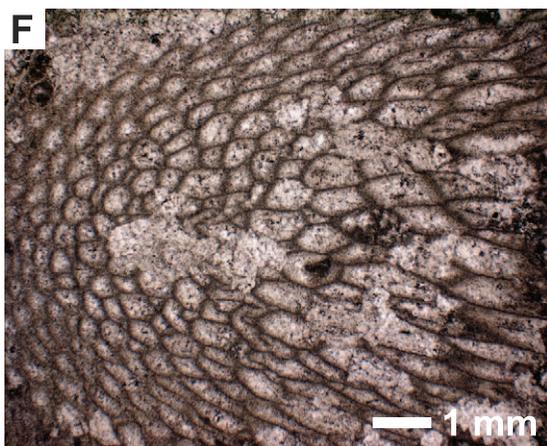
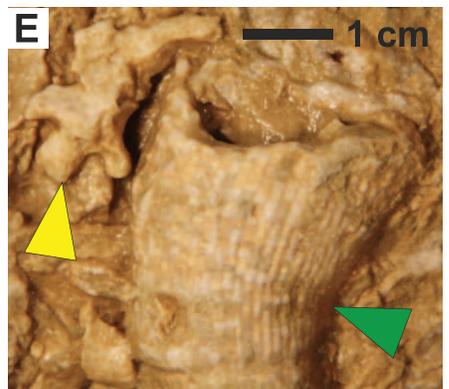
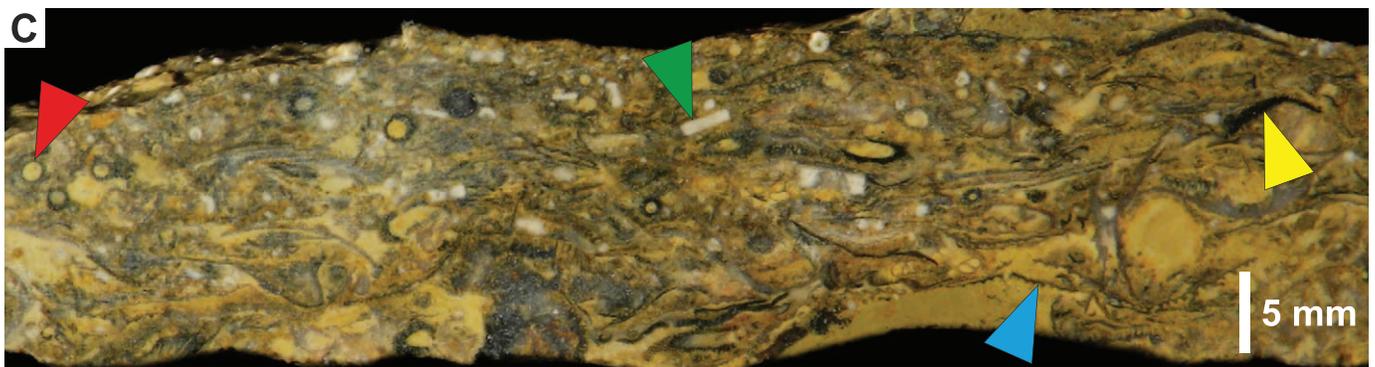
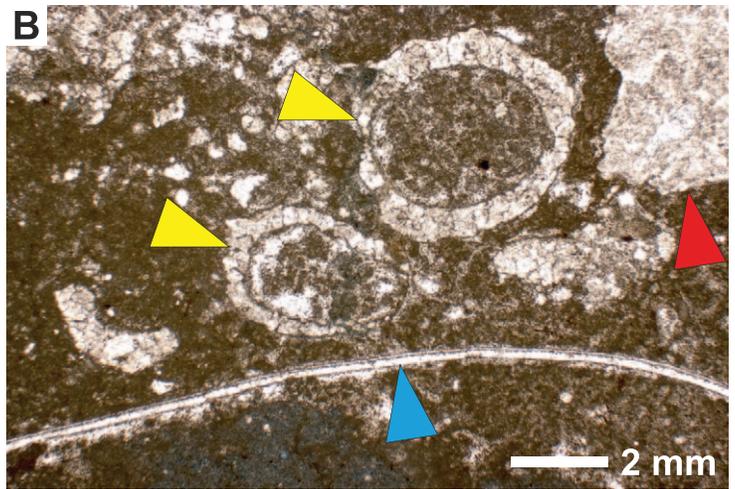
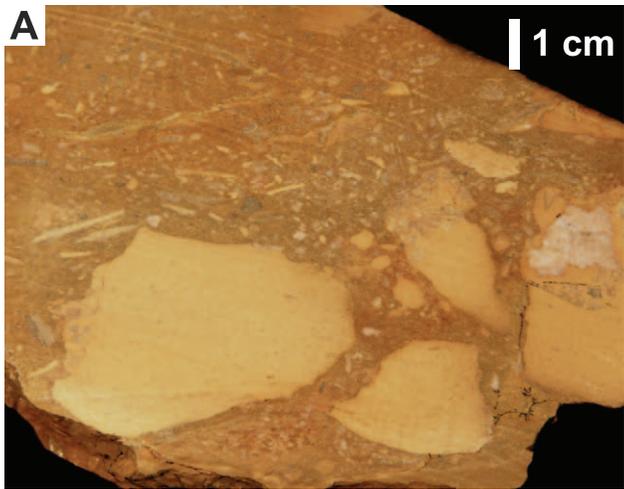
FIG. 7.—Microbial-dominated reef, Dumat Al-Jandal (Locality 5). **A**) Several low-relief mound and conical reefs; car tracks for scale. **B**) Relatively smooth outer surface of columnar stromatolite. **C**) Several mound reefs amalgamated into a single composite mound. **D**) Columnar stromatolite capped by thrombolite. **E**) Thin-section photograph of unusually well-preserved stromatolite microfabric showing alternating dense aphanitic and light microsparitic detrital laminae. Note rounded quartz grains (red arrow) incorporated into the microtexture. **F**) Vertically oriented slab of thrombolite showing greenish micrite (blue arrow) separating irregular, millimetric mesoclots that form irregular clusters (green arrow). **G**) Vertically oriented slab of fine-grained columnar stromatolite with ragged, mutually attached columns.



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FIG. 9.—Metazoan-dominated reef, Wadi Murayr (Locality 8). **A**) Cross section of low-relief subcircular mound. **B**) Irregular columnar stromatolite overgrowing small metazoan–micrite knob on the reef flank (red arrow). **C**) Bedded bryozoan(?) floatstone–rudstone, occupying shelter cavity between two wedge-shaped units of metazoan–micrite framework. **D**) Close view of Part C showing reef framework composed of disordered spiral bryozoan(?) skeletons (bafflestone or rudstone). **E**) Vertically oriented slab of bryozoan(?) bafflestone or floatstone. The space between skeletons (green arrow) is filled by gray micrite (yellow arrow) and greenish microbial impregnations (blue arrow). **F**) Thin-section photograph of Part E, showing epigenetically dolomitized metazoan; septa and their arrangement suggest bryozoan affinity. **G**) Thin-bedded bioclastic packstones adjacent to the reef.



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Received 28 August 2013; accepted 13 October 2014.

APPENDIX: LOCALITIES

Six localities near Dumat Al-Jandal were examined (Fig. 2). Locality 1 (29°48'39.37"N 39°51'59.53"E) is the cliff section immediately below the tower of Mared Castle where several microbial reefs with over-steepened sides are laterally linked and contain numerous small (~ 1 cm)

dissolution vugs in their cores (see Fig. 4E). Localities 2 (29°48'41.49"N 39°51'53.32"E) and 3 (29°48'47.62"N 39°51'39.71"E), respectively, 0.15 and 0.6 km NWW of Mared Castle, show rounded mounds lacking obvious orientation and lacking mesofabric details. They contain vugs in their cores. Locality 4 (29°48'53.05"N 39°51'36.76"E) is 0.8 km NWW of Mared Castle, where two small mesas of Sha'iba Member expose small microbial mounds on their tops. At Locality 5 (29°49'43.83"N 39°49'49.01"E), 4.0 km NWW of Mared Castle, the top of the escarpment has numerous well exposed bioherms each composed of multiple mounds. One small (~ 25 m diameter) bioherm composed of mounds ~ 5 m across was sampled (see Fig. 7). Locality 6 (29°50'58.33"N 39°51'43.86"E), 4.2 km north of Mared Castle, is a well-exposed cliff section of down-faulted Qasr Member, showing a composite bioherm ~ 25 m across with laterally adjacent bedded deposits that contain intraclasts and bioclasts. The bioherm is a group of coalesced domes with over-steepened sides that have flange-like marginal projections (see Fig. 5).

Wadi Murayr, 25–35 km north of Dumat Al-Jandal and ~ 35 km WNW of Sakaka, is a depression that is ~ 5 km W–E and ~ 13 km N–S, mostly enclosed by steep, often cliffed slopes up to ~ 70 m high. It is excavated in the Qasr and Subbat members, and the lowest Hammamiyat limestone forms the main wadi rim. We examined bedding-plane exposures of stromatolitic uppermost Qasr reefs ~ 6 km from the southern end of the wadi (locality 7, 30°04'49.70"N 39°51'06.58"E), and small metazoan reefs up to 3 m thick enclosed and separated by bedded limestone at the mouth of a small NW–SE wadi in a low N–S trending escarpment in the north-central part of Wadi Murayr, ~ 1.5 km south of the north rim (locality 8, 30°06'12.76"N 39°49'00.68"E, see Fig. 9).

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FIG. 10.—Facies adjacent to the reefs. **A**) Vertically oriented slab of intraclast floatstone. Note poor sorting and angular lithoclasts. **B**) Thin-section photograph of Part A, showing green algae (yellow arrows), bivalve (blue arrow), and intraclast (red arrow), in micrite. **C**) Vertically oriented slab of bioclastic floatstone, containing crinoids (green arrow), green algae (red arrow), brachiopods (yellow arrow), and bivalves (blue arrow). **D**) Vertically oriented slab of bioclastic floatstone. Framework is composed of disarticulated bryozoans(?) (blue arrows), whereas the matrix consists of small bivalves. **E**) Surface view of Part D, showing coral (green arrow) and bryozoan(?) fragment (yellow arrow). **F**) Thin-section photograph of Part D, showing bryozoan colony. **G**) Thin-section photograph of peloidal grainstone containing green algae (red arrow) and dissolved small bioclasts (yellow arrow).