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THE MIDDLE EOCENE SEEB FORMATION OF OMAN: AN INVESTIGATION OF ACYCLICITY, STRATIGRAPHIC COMPLETENESS, AND ACCUMULATION RATES IN SHALLOW MARINE CARBONATE SETTINGS

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ABSTRACT: **The middle Eocene Seeb Formation represents deposition on one of the earliest "modern" style carbonate platforms, i.e., influenced by seagrasses and mangroves, and presents an opportunity to explore controls on the preservation of Cenozoic carbonate lithofacies. In the study area, the Seeb Fm. is dominated by an anomalously thick (approximately 250 m) and uniform package of shallow marine, platform-interior sediments. These nodular, indistinctly bedded shallow-subtidal sediments display no evidence for relative sea-level change (such as subaerial exposure features), and lack the shallowing-upwards cyclothems that have characterized carbonate sediments deposited in platform-interior settings throughout much of the rock record (particularly during greenhouse periods). We conclude that this is a consequence of thorough bio-retexturing of the sediment by burrowing organisms and the roots of marine vegetation, which destroyed primary fabrics, facies diversity, evidence for cyclicity, and "missing time" horizons such as cycle-bounding exposure surfaces. It seems possible that the remarkable thickness of apparently acyclic Seeb Fm. sediment that built up may reflect increased bio-disturbance of the shallow marine environment following the Late Cretaceous expansion of seagrasses and mangroves. A similar lack of peritidal cyclothems may be common to many Cenozoic shallow marine carbonate deposits.**

"Missing time" horizons in limestones, reflecting erosion or nondeposition, have been identified by some authors to explain discrepancies between low calculated accumulation rates of ancient sediments and higher rates measured in comparable modern environments. However, our studies of the Seeb Fm. suggest that the significance of such "missing time" horizons in ancient sediments may have been overstated, and that apparent differences between modern and ancient accumulation rates are a consequence of the extrapolation of unrepresentative, localized high rates of modern sediment production to large (platform-scale) areas. Our study reinforces the idea that modern sediment production and accumulation rates may be much lower than previously thought because they are typically measured in highly productive areas such as seagrass beds and do not take into account the highly variable nature of carbonate production, storage, erosion, and destruction across platforms. Therefore, far less "missing time" needs to be inferred for ancient sediments to account for any imbalance between modern and ancient sediment accumulation rates.

INTRODUCTION

Unlike siliciclastic lithofacies, where deposition can result from purely physical processes, carbonate sediments are often the product of complex interactions between physical, chemical, and biological processes. In many shallow platform settings, the small-scale spatial pattern of habitat and carbonate sediment distribution is not that of simple water depth and energy controlled linear belts, but of mosaics (Wilkinson et al. 1999; Wilkinson and Drummond 2004). In addition, many of the different elements (habitats) are not simply related to water depth (Rankey 2004) and are mobile in the sense that one habitat can replace another over short time periods, because of subtle environmental changes. A fundamental question for carbonate sedimentology is to what extent carbonate lithofacies actually record the products of individual environments. It is possible that shallow, platform-interior subtidal litho-microfacies represent "palimpsest sediments, time-averaged and with refractory grains no longer accurately representing their progenitors" (Wright and Burgess 2005).

Another controversial issue relating to shallow-water carbonate sedimentation is that of the disparity between short-term production rates and long-term accumulation rates. The calculated long-term production rates of ancient, shallow marine, low-latitude carbonate sediments are typically much lower than those measured in modern, comparable environments (e.g., Sadler and Strauss 1990; Wilkinson et al. 1991; Schlager 2000). Many studies have assumed that the rate of sediment production in modern, shallow-water carbonate settings (which is a response to rapid, glacioeustatic accommodation creation) is constant over wide areas and is directly applicable to the rock record. The discrepancy between modern and ancient production rates is often attributed to "missing time" in the ancient sediments, reflecting sediment erosion and/or periods of regional nondeposition. However, recent

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studies have shown that sedimentation in shallow marine, low-latitude carbonate environments is far from uniform across platforms, occurring as a complex mosaic of sediment production (e.g., Enos 1991; Demicco and Hardie 2002; Wilkinson and Drummond 2004; Yang et al. 2004). The various elements of this mosaic are mobile over short timescales, suggesting that facies deposited as such mosaics are preserved as overprinted and time-averaged successions in the rock record, exhibiting far less complexity than exists at the modern sediment–water interface (Wright and Burgess 2005). Modern sediment accumulation rates appear to be lower than has been previously assumed (e.g., Demicco and Hardie 2002; Wilkinson and Drummond 2004; Yang et al. 2004), questioning the importance of "missing time" horizons in ancient sediments.

Solving issues such as whether litho-microfacies represent original habitats, and the causes of "missing time," are beyond the scope of a single study. However, this study of the middle Eocene Seeb Fm. of Oman brings these issues sharply into focus. The Seeb Fm. was deposited in a tropical, shallow marine setting, dominated by larger benthic foraminifera (LBF)—particularly *Alveolina* and the nummulitids *Nummulites* and *Assilina*. It displays remarkable uniformity, typically occurring as a thick succession of nodular, poorly bedded sediments that lack facies diversity and exhibit little evidence for high-frequency facies or sea-level change (such as peritidal cyclothems and exposure surfaces), and presents problems in terms of understanding the interplay between accommodation-space creation and sediment production. We describe and interpret Seeb Fm. lithofacies in detail, and discuss sediment accumulation and the development and preservation of facies.

Using modern analogs for interpreting ancient successions is especially difficult in carbonates where evolutionary changes have produced widely different biotic compositions. In addition, a cautious approach is needed when comparing shallow marine carbonate sediment accumulation under modern icehouse conditions (characterized by high-amplitude sea-level fluctuations) with ancient successions such as the Seeb Fm., deposited during greenhouse periods (affected by significantly lower-amplitude sea-level changes). During the former, there may be insufficient time to fill available accommodation space before a glacially induced sea-level lowstand terminates sediment production, resulting in thick (5–10 m) packages of subtidal sediment capped by marked subaerial exposure surfaces; in the latter there may be time for sediment to build to sea level, resulting in meter-scale, shallowing-upwards peritidal cycles (Wright 1992; Fournier et al. 2004; Purdy and Gischler 2005). However, the Seeb Fm. is an attractive case study to assess just what enters the fossil record, because it is one of the earliest demonstrably modern-type successions: it is associated with mangrove coastlines and seagrasses, two key elements of modern platform-interior systems.

GEOLOGICAL SETTING

The middle Eocene Seeb Fm. crops out on the Batinah Coast of northern Oman and is also locally present on the west flank of the Oman Mountains (Fig. 1). The study area is located near Al Khod (Fig. 1) and comprises an Eocene succession of sediments deposited after the Late Cretaceous obduction of the Semail Ophiolite (Nolan et al. 1990). Evidence from paleogeographic and climate modeling suggests that these sediments were deposited within the tropics (close to 12° N), on a windward coast facing a large expanse of open ocean towards the east (Valdes et al. 1999; Dercourt et al. 2000). The lithostratigraphy of post–ophiolite obduction sediments deposited on the Batinah Coast during the Late Cretaceous and early Tertiary is shown in Figure 2. Late Campanian and Maastrichtian sediments are dominantly beach, fluviatile, and fan-delta deposits (e.g., the Al Khod Fm.) (Nolan et al. 1990). However, subsequent widespread carbonate deposition, and a marked decrease in the amount of siliciclastic material in latest Cretaceous and early Tertiary sediments, suggest that the Oman Mountains were submerged during this period (Nolan et al. 1990; Skelton et al. 1990). Cretaceous and Tertiary strata in the Oman Mountains are separated by a major regional unconformity, which is overlain in both the northeast and southwest parts of the central Oman Mountains by shallow marine carbonates of the late Paleocene to early Eocene Jafnayn Fm. (Nolan et al. 1990). On the Batinah Coast (Fig. 1) a marked non-sequence separates the Jafnayn Fm. from overlying fluvial and lagoonal deposits (associated with mangroves) of the early Eocene to earliest middle Eocene Rusayl Fm. (Keen and Racey 1991; Racey 1995). A marine transgression during the middle Eocene resulted in deposition of the open marine Seeb Fm. across the central Oman Mountains (over a period of approximately 7.8 My, between the basal middle Eocene (global biostratigraphic zone [GBZ] NP15) and the earliest upper Eocene (GBZ NP18; Jones and Racey 1994). Nolan et al. (1990) noted that the contact between the Seeb and Rusayl formations is sharp but conformable, although the memoir to geological map NF40-03 (Seeb sheet, 1992; Sultanate of Oman, Ministry of Petroleum and Minerals), states that the lack of both the underlying Rusayl and Jafnayn formations in the area to the south of Khasaf, where the Seeb Fm. directly overlies the Cretaceous Thaqab Fm., indicates a disconformity, and Racey (1995) noted that a patchily developed limestone conglomerate horizon, notably at Wadi Rusayl, may indicate a minor non-sequence. Nolan et al. (1990) suggest that the Seeb Fm. is almost certainly overlain by a regional unconformity that separates Eocene and Oligo-Miocene strata on the Arabian Peninsula (although it is not exposed) and note that it locally interfingers with slope deposits (calcarenites, conglomerates, chalky limestones, and marls) of the Ruwaydah Fm.

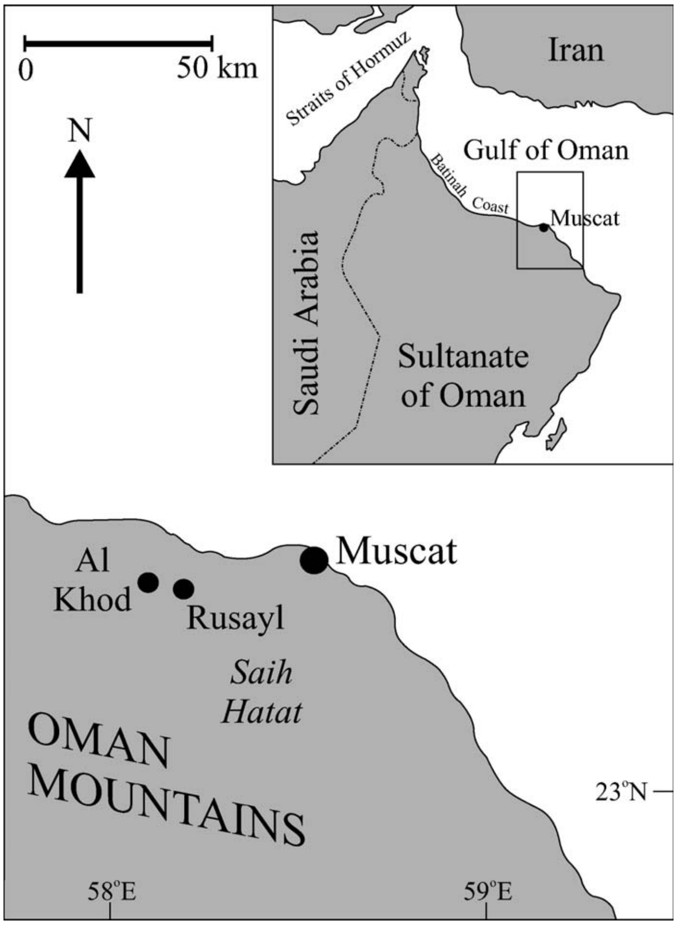


FIG. 1.— Map of NE Oman, showing position of the study area at Al Khod. Location of the main map is shown on the inset.

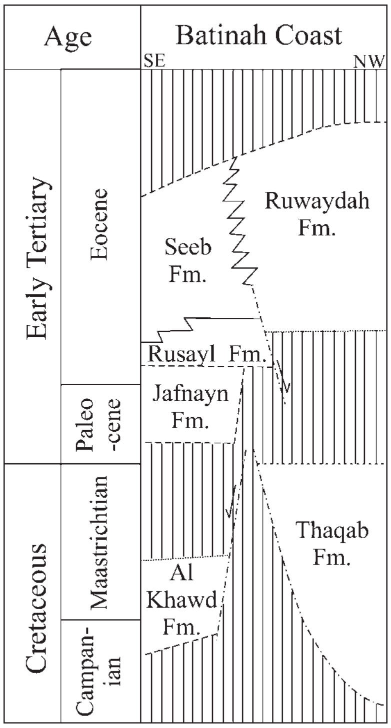


FIG. 2.—Lithostratigraphy of Campanian to Eocene sediments on the Batinah Coast (modified from Nolan et al. 1990)

Lateral facies variations within these Late Cretaceous and early Tertiary formations are especially noticeable along the Batinah Coast and have been attributed to syndepositional movements along an extensional fault system that was initiated during emplacement of the ophiolite (S. Nolan, personal communication in Racey 1995).

PREVIOUS WORK ON THE SEEB FORMATION

Several studies have described the lithostratigraphy and biostratigraphy of the Seeb Fm., focusing mainly on the type section at Wadi Rusayl (Fig. 1), e.g., Nolan et al. (1990) and Racey (1994, 1995, 2001). These studies suggest that the Seeb Fm. was deposited on a storm-influenced ramp and note that for much of its extent it is characterized by a transgressive package of limestones up to 350 m thick, which display a vertical trend in foraminiferal content, with alveolinids and miliolids dominating basal sections, whilst younger sections are characterized by an association of nummulitids (*Nummulites* and *Assilina*) and the orthophragminid *Discocyclina*. The nummulitids commonly occur as low-amplitude (biostromal) banks, 100–200 m long and 1–10 m thick, which thin towards the flanks (Racey 2001). The Seeb Fm. thins towards the northwest along the Batinah Coast (at least as far as Khasaf, approximately 120 km WNW of Wadi Rusayl), accompanied by a decrease in content of carbonate mud and the local development of coral–algal patch reefs.

METHODS

Much of the Seeb Fm. within the field area is covered in Pliocene–Quaternary alluvial gravel, so study focused on outcrops exposed in a road cut near Al Khod village and close to Sultan Qaboos University (SQU) (see Fig. 3), and also an almost complete (and previously unstudied) section through the Seeb Fm. exposed in Wadi Al Khod. Lateral variability and geometry and architecture of LBF (*Nummulites* and *Assilina*) accumulations identified in the youngest sections of Seeb Fm. in the wadi were assessed by correlation with outcrops of the same age and facies near SQU.

The limestones of the Seeb Fm. are dominated by LBF (particularly nummulitids), and these were the focus of quantitative and biofabric analysis. Lithofacies were differentiated and characterized on the basis of visual estimates (using published charts; e.g., Baccelle and Bosellini 1965) of all allochems and matrix in thin sections and acetate peels. Lithofacies subdivisions have been further refined through detailed analysis of the nummulitid LBF component, including: (1) an assessment of the autochthonous or allochthonous nature of the nummulitid tests (based upon a comparison with the taphonomic criteria defined by Beavington-Penney (2004), for the recognition of *in situ* and transported *Nummulites* in thin section); (2) the number of intact (and therefore *in situ*) *Nummulites* present (and their density per cm^2); (3) test size and shape; (4) the ratio of megalospheric (A-form) to microspheric (B-form) *Nummulites*; and (5) the texture and biofabric of the rock. The ratio of A-forms to B-forms provides useful paleoenvironmental information, because studies of modern dimorphic LBF indicate that A-forms (the asexual generation) dominate in the shallowest and deepest parts of a specific depth range, whilst B-forms (the larger, sexual generation) are most common at intermediate depths (e.g., Leutenegger 1977; Hottinger 1982, 1997). Biofabrics of nummulitic sediments were described and interpreted using the criteria presented in Beavington-Penney et al. (2005) (see Fig. 4). Fragmented or abraded (i.e., allochthonous) *Nummulites* were divided into three size categories: *Nummulites* fragments (> 1.3 mm); nummulithoclastic debris (< 1.3 mm and > 0.2 mm); and fine nummulithoclastic debris (< 0.2 mm).

Numerous studies of both modern and ancient LBF have shown changes in associations of depth-sensitive, symbiont-bearing larger foraminifera along environmental gradients (e.g., Ghose 1977; Hohenegger et al. 1999; Geel 2000; Renema and Troelstra 2001), and such studies have been used to assist relative paleobathymetric and paleoenvironmental comparison between LBF associations within the Seeb Fm. Morphological characteristics of *Nummulites* tests, e.g., diameter/thickness (D/T) ratio, have also been used to refine facies subdivisions and/or interpret depositional environments of facies inferred to represent paleocommunities (i.e., autochthonous or parautochthonous assemblages; cf. Brenchley and Harper 1998). Studies of living nummulitids and other symbiont-bearing LBF have clearly shown that there is a trend of test-shape change with water depth (e.g., Larsen 1976; Hallock 1979). Within taxa, tests from deep-photic-zone environments are much flatter than those from shallow, brightly lit water. We have used relative differences in D/T measurements of *Nummulites* from the Seeb Fm. to assist paleobathymetric comparison between facies. Such analysis is based only on data from A-form *Nummulites*, because the B-form data set is significantly smaller, mainly due to their large test size and hence reduced number per thin section. However, inferences based on the morphological characteristics of A-form *Nummulites* have been made with caution, because D/T measurements can be made only where a true axial section of the test is exposed, and, because the number of suitable tests per thin section or peel is limited, data sets are often small. Although variations in such data can be due to the presence of a number of species with a wide range of D/T values, comparison of "winding diagrams" (measurements of the increase in radius per whorl) and other morphological characteristics with published data (Schaub 1981; Racey 1995) suggests that *Nummulites* accumulations at Wadi Al Khod consist of a single species, identified as *N. deshayesi* (Beavington-Penney 2002). Similar results were published by Racey (1994, 1995, 2001), who concluded that *Nummulites* "banks" at Wadi Rusayl are dominated by one or two large species from the groups *N. perforatus* (of which *N. deshayesi* is part) and *N. gizehensis*.

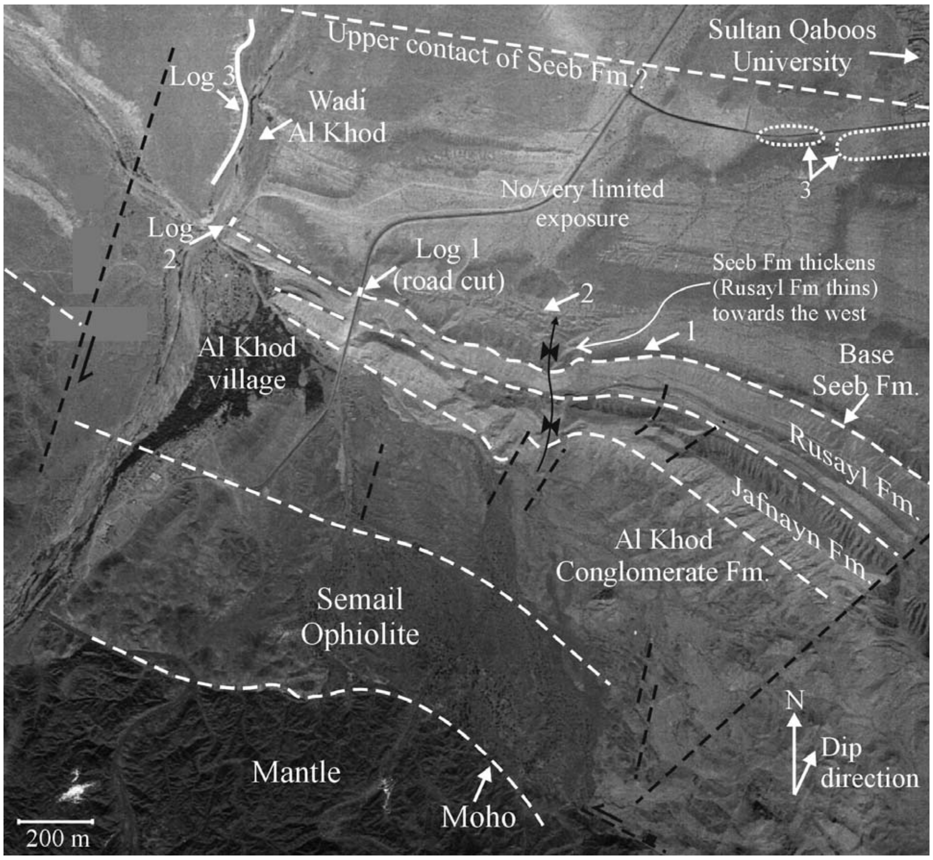


FIG. 3.— Aerial photograph of field area, showing positions of studied sections. Information on formation boundaries (dashed white lines) is taken from Seeb geological map (sheet NF 40-03), and also S. Hanna, personal communication 2002. Structural features (dashed black lines) courtesy of S. Hanna, personal communication 2004. Numbered locations are referred to in later text.

FACIES AND THEIR INTERPRETATION

Detailed macrofacies and microfacies descriptions and biometric data are presented in Table 1. Facies distribution throughout Wadi Al Khod is illustrated in summary logs in Figure 5. Microfacies characteristics are illustrated in Figures 6 and 7, and key macrofacies features are shown in Figures 8, 9, and 10. Textural classification follows Dunham (1962) and Mount (1985). Facies are interpreted below and then are grouped into associations and integrated into an overall depositional model.

As can be seen in Figures 5 and 8A, the Rusayl Fm. is interbedded with the Seeb Fm. at the base of the studied section. The Rusayl Fm. is not described in detail in this study, because it has already been the subject of several sedimentological and palynological studies (e.g., Keen and Racey 1991; Racey 1995), and its paleoenvironmental setting of fluvial and lagoonal deposits associated with mangroves is well understood.

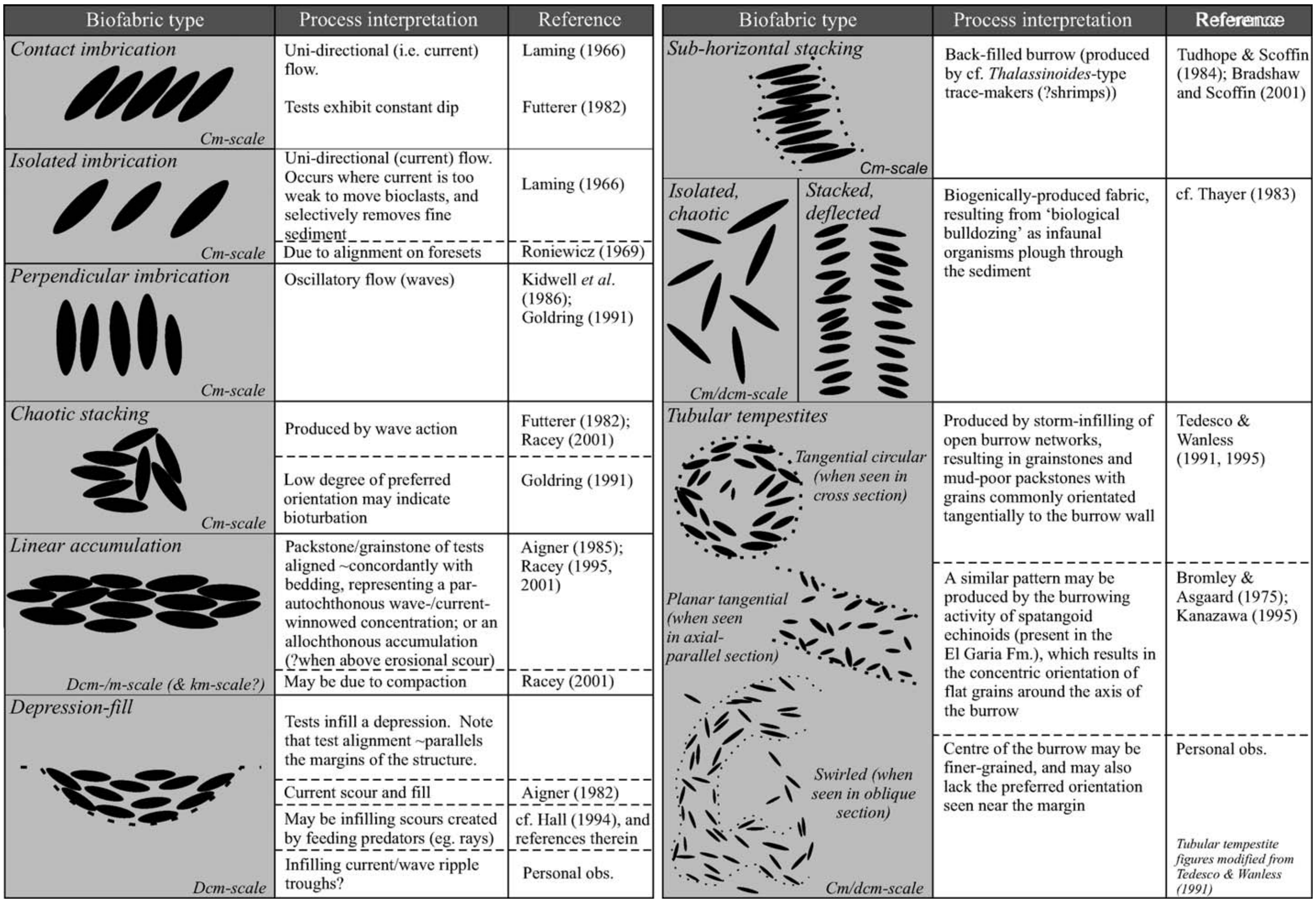
Facies 1. Quartzose, Red Algal–Peloidal–Foraminiferal Grainstone

Decimeter- to meter-scale packages of Facies 1 are interbedded with Facies 2, 3, and 5A, and also with the Rusayl Fm (see Figs. 5, 8A). Petrographic study of the quartz in this facies (Beavington-Penney 2002) suggests a probable metamorphic origin, and it may therefore represent reworked sediment eroded from the Oman Mountains before they were submerged during the latest Cretaceous, or perhaps during temporary reemergence during the early Eocene, possibly from the closest contemporary source at Saih Hatat (see Fig. 1 for location).

Paleocurrents obtained from cross-bedding in this facies (illustrated in Fig. 8B) suggest a bimodal (i.e., tidal) component (Table 1), although the fan-shaped rose plot of these paleocurrents (Beavington-Penney 2002) may be indicative of secondary currents, perhaps a consequence of flow divergence after passing through a constriction (cf. Anastas et al. 1997). Alternatively, it may be due to wind influence, or the formation of separate flows at the front of bed forms, or perhaps changes in current direction late in tidal semicycles (Gonzalez and Eberli 1997, and references therein), or it may be an artifact of the 3-D nature of foresets (Berné et al. 1991). A shallow marine setting during deposition of Facies 1 is also suggested by the presence of (probable) swaly cross stratification (SCS; Fig. 8C), which is generally considered to form in the shoreface zone during storm events (Tucker and Wright 1990, p. 108, and references therein). Whilst cements present in this facies (such as isopachous fringes of non-ferroan calcite) are generally interpreted as being of marine phreatic origin, rare (possible) dripstone cements may indicate deposition in the intertidal zone (Beavington-Penney 2002).

Biofabrics in this facies, including "contact imbrication" and "isolated imbrication" (see Fig. 4), as well as the strong degree of preferred orientation exhibited by many grains (Fig. 6A), also suggest deposition in a high-energy, current-dominated environment. Such a setting is also indicated by the highly abraded state of many of the bioclasts.

Foraminifera in Facies 1, such as alveolinids, miliolids, soritids, peneroplids, orbitoids, and encrusting foraminifera, are a typical shallow marine assemblage (see below). Other common bioclasts include fragments of both articulated and foliose crustose forms of coralline red algae (CRA). The former indicates deposition in the shallow marine realm, because these forms generally reach their maximum abundance in water < 10 m deep, in intertidal (or other high-energy) regimes (Wray



Biofabric type	Process interpretation	Reference
Contact imbrication (Cm-scale)	Uni-directional (i.e. current) flow.	Laming (1966)
	Tests exhibit constant dip	Futterer (1982)
Isolated imbrication (Cm-scale)	Uni-directional (current) flow. Occurs where current is too weak to move bioclasts, and selectively removes fine sediment	Laming (1966)
	Due to alignment on foresets	Roniewicz (1969)
Perpendicular imbrication (Cm-scale)	Oscillatory flow (waves)	Kidwell *et al.* (1986); Goldring (1991)
Chaotic stacking (Cm-scale)	Produced by wave action	Futterer (1982); Racey (2001)
	Low degree of preferred orientation may indicate bioturbation	Goldring (1991)
Linear accumulation (Dcm-/m-scale (& km-scale?))	Packstone/grainstone of tests aligned ~concordantly with bedding, representing a par-autochthonous wave-/current-winnowed concentration; or an allochthonous accumulation (?when above erosional scour)	Aigner (1985); Racey (1995, 2001)
	May be due to compaction	Racey (2001)
Depression-fill (Dcm-scale)	Tests infill a depression. Note that test alignment ~parallels the margins of the structure.	
	Current scour and fill	Aigner (1982)
	May be infilling scours created by feeding predators (eg. rays)	cf. Hall (1994), and references therein
	Infilling current/wave ripple troughs?	Personal obs.

Biofabric type	Process interpretation	Reference
Sub-horizontal stacking (Cm-scale)	Back-filled burrow (produced by cf. *Thalassinoides*-type trace-makers (?shrimps))	Tudhope & Scoffin (1984); Bradshaw and Scoffin (2001)
Isolated, chaotic *Stacked, deflected* (Cm/dcm-scale)	Biogenically-produced fabric, resulting from 'biological bulldozing' as infaunal organisms plough through the sediment	cf. Thayer (1983)
Tubular tempestites *Tangential circular (when seen in cross section)*	Produced by storm-infilling of open burrow networks, resulting in grainstones and mud-poor packstones with grains commonly orientated tangentially to the burrow wall	Tedesco & Wanless (1991, 1995)
Planar tangential (when seen in axial-parallel section)	A similar pattern may be produced by the burrowing activity of spatangoid echinoids (present in the El Garia Fm.), which results in the concentric orientation of flat grains around the axis of the burrow	Bromley & Asgaard (1975); Kanazawa (1995)
Swirled (when seen in oblique section) (Cm/dcm-scale)	Centre of the burrow may be finer-grained, and may also lack the preferred orientation seen near the margin	Personal obs.

Tubular tempestite figures modified from Tedesco & Wanless (1991)

FIG. 4.—Key *Nummulites* biofabric types, summarized from published work on the fabric of nummulitic limestones, and also sediments containing comparable grains (e.g., centimeter-scale *Halimeda* grains in the bioturbated and storm-swept mud mounds of Florida Bay), and also from personal observations. Figure modified from Beavington-Penney et al. (2005), and summarized from Laming (1966), Roniewicz (1969), Bromley and Asgaard (1975), Aigner (1982, 1985), Futterer (1982), Thayer (1983), Tudhope and Scoffin (1984), Kidwell et al. (1986), Goldring (1991), Tedesco and Wanless (1991, 1995), Hall (1994), Kanazawa (1995), Racey (1995, 2001), and Bradshaw and Scoffin (2001).

1977); a shallow marine origin is also postulated for the foliose crustose CRA (see below). The presence of halimedacean and dasycladacean calcareous green algae reinforces this interpretation, because, whilst halimedaceans are common from the low tide mark to the base of the photic zone, dasycladaceans are generally found only down to 30 m and reach their maximum abundance in water shallower than 5 m (Wray 1977) (although, unlike CRA, both prefer low-energy regimes). The partial to complete micritization of many of the grains suggests that much of the sediment is allochthonous, because it seems unlikely that infestation of the bioclasts by microendolithic organisms would have occurred in such high-energy conditions.

To summarize, Facies 1 represents the deposition of an allochthonous grainstone, composed of a diverse shallow-water biota and reworked quartz, in a high-energy, shallow marine environment (shoreface, or perhaps foreshore), probably influenced by storms, tidal currents, and waves.

Facies 2. Nodular Foraminiferal–Red Algal Packstone (Locally Grainstone)

Facies 2 exhibits poorly defined, nodular, decimeter- to meter-scale bedding and is interbedded with Facies 1, 3, and 4, but it is most commonly associated with Subfacies 5-A (Fig. 5). The bulk of this facies consists of poorly sorted packstones, with up to 50% micrite, suggesting a low-energy regime, supported by the presence of occasional articulated, thin-walled bivalves, common burrows, and biogenically produced biofabrics (e.g., "isolated chaotic;" see Fig. 4) and calcareous green algae (especially dasycladaceans). However, the occasional occurrence of "depression-fill" biofabrics may indicate periodic scouring during higher-water-energy events (Fig. 5).

This facies contains a highly diverse, shallow marine biota. The most abundant bioclasts are CRA, including fragments of both articulated and crustose types, the former indicating deposition in shallow water (< 10 m). The latter includes distinctive foliose crusts, up to 3.26 mm long and 0.16 mm thick, with one flat (?attachment) surface and often with a hooked termination at one end (Fig. 6E; also see Figs. 6F and 7D which illustrate hooked foliose CRA in Facies 3 and 5A, respectively). Identical hook-shaped CRA with a flat attachment surface have been identified growing on modern seagrasses (their morphology a consequence of growth over the leaf margin) and are considered to be definitively indicative of formerly vegetated environments when identified in ancient sediments (Beavington-Penney et al. 2004). The influence of marine vegetation during deposition of this facies is also suggested by the presence of tubular fragments of crustose CRA, and (rare) "constructive" micrite envelopes (a micritic layer associated with a grain surface that shows no obvious signs of microboring, documented from modern

TABLE 1.—*Macrofacies and microfacies descriptions, and biometric data of* in situ Nummulites *tests. Percentages of the various components have been averaged from numerous samples; spreadsheets of the full data set for both facies composition and* Nummulites *biometry are available from the first author on request. Size categories for fragmented* Nummulites *are shown in Methodology section.*

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	Macrofacies & larger foraminiferal biofabrics	*Nummulites* biometrics
Facies 1. Quartzose, red algal–peloidal–foram grainstone Fragments of crustose and articulated CRA (including *Distichoplax biserialis*) (21.3%); peloids (9.8%); quartz (6.8%); *Alveolina*, including juvenile forms (3.5%); miliolids (2.3%); unidentified skeletal fragments (4.9%); minor components: *Nummulites* fragments, nummulithoclastic debris, *Somalina* sp., soritids (including *Orbitolites* sp.), small rotaliids (including *Linderina* sp.), small orbitoids, peneroplids, ?encrusting foraminifera (including cf. *Eorupertia*), textulariids, echinoids, bryozoans, halimedacean and dasycladacean green algae, gastropods, ostracods, bivalves, and phosphate. Fig. 6A, B.	Bedded on a decimeter to meter scale; occasionally exhibits an erosional basal contact. Low-angle, tabular & herring bone cross bedding is common Fig. 8B (paleocurrents exhibit a dominant bimodal NW–SSE -trend; Beavington-Penney, 2002). Probable SCS is locally present Fig. 8C. Beds are occasionally nodular, with rare horizontal & vertical burrows. This facies is laterally continuous along the ridge marked "1" on Fig. 3 for at least 1.8 km. Biofabrics: "contact imbrication" and "isolated imbrication;" grains exhibit a strong degree of preferred orientation.	**A:B ratio**: Intact *Nummulites* are commonly absent. Where present only A-forms occur (in very low numbers) **Density**: A-form av. = 0.04/cm^2.
Facies 2. Nodular foram–red algal packstone (locally grainstone) Micrite (0–50%); articulated & foliose/tubular CRA (9.1%); peloids (6.4%); quartz (2.5%); ?encrusting foraminifera (including *Eorupertia* sp. & *Fabiania* sp.) (4.3%); *Nummulites* (3%); dasycladacean algae, including cf. *Furcoporella* sp. (2.8%); *Alveolina* (2.4%); milioids (2%); echinoid fragments (1.9%); gastropods (1.5%); unidentified skeletal fragments (10.6%); bivalves (1.4); minor components: *Nummulites* fragments, A-form *Assilina*, small rotaliids (including *Linderina* sp.) & other SBF, larger rotaliids (including *Lockhartia hunti* & *Dictyoconoides* sp.), textulariids, soritids (including *Orbitolites* sp.), peneroplids, *Somalina* sp., ostracods, halimedacean algae, bryozoans, coral fragments, phosphate, glauconite, & finely crystalline dolomite (in abundances of up to 15%). Rare grains exhibit "constructive" micrite envelopes (cf. Perry, 1999). Fig. 6C, D, E.	Typically exhibits poorly-defined, nodular, decimeter- to meter-scale bedding Fig. 8D. Horizontal and vertical burrows, commonly filled by coarse bioclastic debris, are relatively abundant, and "isolated chaotic" biofabrics are common. Scours are locally evident; these are usually decimeter-wide, several centimeter deep, & are also filled by coarse bioclastic material. A diverse macrofaunal community is observable in the field, including intact gastropods & echinoids, and articulated and disarticulated bivalves.	**A:B ratio**: Locally no *Nummulites* are present; occasional dense clusters of A-form tests occur; where B-forms occur the ratio varies from 3:1 to 32:1. **Density**: A-form av. = 0.55/cm^2; B-form av. = 0.32/cm^2. **Test size/shape**: A-form D/T av. = 2.28 mm; SD = 0.31; n = 6.
Facies 3. A-form *Nummulites*-dominated peloidal–red algal packstone *Nummulites praediscorbinus* (11.3%); peloids, (18.3%); quartz (8%); articulated & foliose crustose CRA (7.7%); miliolids (3.8%); echinoids (3%); unidentified skeletal fragments (2.3%); minor components: encrusting forams (including *Eorupertia*, *Eofabiania* & *Fabiania*), soritids (including *Orbitolites*), small rotaliids, textulariids, ostracods, dasycladacean algae, rare *Discocyclina*, *Lockhartia* sp., *Nummulites* fragments, nummulithoclastic debris, bivalves, bryozoans, & phosphate. Fig. 6F.	Bedded on a decimeter scale. Beds are nodular, with common large *Thalassinoides* burrows containing dense accumulations of A-form *Nummulites*. Evidence from outcrops (location "2" on Fig. 3) suggests that although widespread, this unit is laterally discontinuous, forming sheet-like sandbodies, hundreds of meters in width. Biofabrics: "isolated chaotic," "sub-horizontal stacking," "tangential circular," & "planar tangential."	**A:B ratio**: Only A-forms are present **Density**: A-form av. = 9.48/cm^2. **Test size/shape**: A-form D/T av. = 1.87 mm; SD = 0.22; n = 12.
Microfacies descriptions	Macrofacies & larger foraminiferal biofabrics	*Nummulites* biometrics
Facies 4. Nodular foram–algal packstone (locally wackstone) Crustose CRA (foliose, 3.9%; rhodoliths, 1.4%); articulated CRA (2.9%); peloids (4.1%); *Nummulites cuvillieri* & *Nummulites* spp. (3.2%); *Nummulites* fragments (2.3%); *Alveolina* (2.4%); encrusting forams, including *Eorupertia* sp. & *Fabiania* sp. (2.6%); miliolids (1.4%); textulariids (1.2%); echinoids (2.0%); dasycladacean algae (1.6%); bivalves (1%); unidentified skeletal fragments (10.1%); quartz (1.5%); micrite (15–55%); minor components: n'clastic debris, *Assilina*, *Somalina* sp., *Discocyclina*, larger rotaliids (including *Lockhartia* sp. & *Dictyoconoides* sp.), peneroplids, small rotaliids & other SBF, ostracods, bryozoans, gastropods, corals, phosphate, intraparticle glauconite and ?siderite, halimedacean algae, peyssonnelid algae (cf. *Ethelia* sp.), soritids (including *Orbitolites* sp.), & dolomite (locally up to 13%). Fig. 6G, H, 7A, B.	Nodular, & lacks well-defined bedding Fig. 9A, B. *Thalassinoides* & ?*Planolites* burrows are common Fig. 9C. Gypsum is (rarely) present along bedding planes. Outcrops south of SQU (location "3" in Fig. 3) suggests this facies is laterally continuous for at least 2 km. Macrofauna include large gastropods & spatangoid echinoids. Rare clusters of teredinid tubes (up to 2 m long; bedding-parallel) are present. Biofabrics: "isolated chaotic," "subhorizontal stacking," "contact imbrication," "depression fill," "tangential circular," & "planar tangential." LBF often parallel to subparallel to nodule margins.	**A:B ratio**: Commonly only A-forms are present; where B-forms occur the ratio varies from 1:1 to 20:1. **Density**: A-form av. = 0.96/cm^2; B-form av. = 0.03/cm^2. **Test size/shape**: A-form D/T av. = 2.08 mm; SD = 0.31; n = 60.
Subfacies 5-A. Quartzose peloidal grainstone Quartz (11.6%); peloids and abraded CRA (undifferentiated; 19.7%); unidentified skeletal fragments (4.9%); miliolids (including *Quinqueloculina* sp.) (1.4%); minor components: alveolinids, textulariids, peneroplids, small rotaliids & other SBF, soritids (including ?*Orbitolites*), ?encrusting foraminifera (including cf. *Eofabiania* and cf. *Eorupertia*), bryozoans, dasycladacean algae, ostracods, bivalves, echinoids, phosphate, & glauconite; locally dense accumulations of CRA occur, composed of up to 12% articulated forms and up to 16% foliose crustose forms. Fig. 7C, D.	Bedded on a decimeter to meter scale, with beds varying between 0.2 and 1.4 m thick. Local ?loading structures are evident, and upper contacts are often bioturbated. Beds are generally massive, although occasional cm-scale lamination is evident.	

TABLE 1.—Continued.

Microfacies descriptions	Macrofacies & larger foraminiferal biofabrics	*Nummulites* biometrics
Subfacies 5-B. Sandy peloidal limestone Quartz (33.3%); peloids and rounded grains of CRA (25.5%); minor components: *Nummulites*, *Alveolina*, miliolids, small rotaliids and other SBF, ?encrusting forams (including cf. *Eorupertia*), disarticulated ostracods, echinoids, bivalves, dasycladacean algae, and phosphate.	Bedded on a decimeter-/meter-scale, with beds 0.5 to 1.2 m thick. Basal scoured contact is overlain by a lag (up to 4 cm thick) of intact & fragmented LBF tests (dominantly *Alveolina*). The upper contact is bioturbated. Beds are generally massive, although locally nodular, and occasionally exhibit poorly defined tabular cross-stratification.	**A:B ratio**: Commonly *Nummulites* are absent; where present only A-forms occur (in very low numbers) **Density**: A-form av. = 0.10/cm^2
(*Facies 5 is subdivided on the basis of quartz content, sedimentary structures, and associated facies*).		
Subfacies 6-A. *Nummulites* wackestone *Nummulites* spp. (14.7%); *Nummulites* fragments (5%); n'clastic debris (4%); peloids (2.3%); micrite (40–50%); soritids (including ?*Orbitolites*) (1.7%); *Alveolina* (2%); miliolids (1.7%); textulariids (1.5%); encrusting forams (1.2%); irregular echinoids (1.7%); articulated CRA (1.3%); crustose CRA (1.7%); dasycladacean algae (1.7%); dolomite (2.7%); unidentified skeletal fragments (3%); minor components: *Assilina* & *Discocyclina*, small rotaliids & other SBF, ostracods & quartz. *Nummulites* occasionally exhibit "constructive" micrite envelopes. Fig. 7E.	Bedded on a decimeter to meter scale, although bedding is indistinct. Locally nodular, and horizontal burrows (infilled by intact and fragmented LBF) are common. Outcrop study (the area marked "3" in Fig. 3) suggest that this facies is laterally continuous for at least 2 km. Macrofauna present includes echinoids, gastropods, & oysters. Biofabrics: "isolated chaotic," "contact imbrication," & "tangential circular."	**A:B ratio**: Commonly only A-forms occur; locally ratios vary from 17:1 to 21:1. **Density**: A-form av. = 1.91/cm^2; B-form av. = 0.06/cm^2. **Test size/shape**: A-form D/T av. = 1.65 mm; SD = 0.20; n = 11.
Subfacies 6-B. *Nummulites–Assilina* packstone *Nummulites* spp. (7%); *Nummulites* fragments (12%); n'clastic debris (10%); *Assilina spira spira* & *Assilina* sp. (intact & fragmented (11%); *Discocyclina* (intact & fragmented) (4.3%); micrite (< 35%); echinoids (2.7%); oysters (2%); minor components: soritids, miliolids, textulariids, ?encrusting foraminifera, SBF, ostracods, bryozoa, coral fragments, crustose CRA, dasycladacean algae, peloids, and dolomite (locally 14%). The ratio of *Nummulites* to *Assilina* is highly variable. Fig. 7F.	Indistinctly bedded on a meter scale. Outcrop study (the area marked "3" in Fig. 3) suggests that this facies forms sheet-like bodies, up to 7 m thick & several hundred meters long, which grade into Facies 5 along strike. Biofabrics: "linear accumulation," "contact imbrication," "chaotic stacking," "subhorizontal stacking," & rare "isolated chaotic" Fig. 10B.	**A:B ratio**: ratios vary locally from 28:1 to 2:1. **Density**: A-form av. = 0.64/cm^2; B-form av. = 0.04/cm^2. **Test size/shape**: A-form D/T av. = 1.75 mm; SD = 0.17; n = 29.
Subfacies 6-C. *Nummulites–Discocyclina* wackestone–packstone *Nummulites* spp. (7.7%); *Nummulites* fragments (5.7%); n'clastic debris (3.3); *Discocyclina* (6.7%); micrite (47.7%); unidentified skeletal fragments (4.5%); dasycladacean algae (1.8%); minor components: soritids (including cf. *Orbitolites* sp.), nummulitids (cf. *Spiroclypeus granulosus*), alveolinids, miliolids, textulariids, ?encrusting foraminifera (including cf. *Fabiania* sp.), small rotaliids (including *Linderina* sp.) & other SBF, echinoids, ostracods, bryozoans, bivalves, gastropods, CRA, peloids, phosphate, coral fragments (locally 13%), & dolomite (locally 17%). Fig. 7G.	Indistinctly bedded on a meter scale. Common burrows, including (rare) pelleted burrows (cf. *Ophiomorpha*). Outcrop study (the area marked "3" in Fig. 3) suggests this facies is laterally continuous for at least 2 km. Macrofauna includes echinoids & high-spired gastropods. Biofabrics: "subhorizontal stacking," "isolated chaotic," "tangential circular," "planar tangential," &, rarely, "contact imbrication" Fig. 10C, D.	**A:B ratio**: Commonly only A-forms occur; locally ratios vary from 7:1 to 28:1. **Density**: A-form av. = 1.23/cm^2; B-form av. = 0.06/cm^2. **Test size/shape**: A-form D/T av. = 1.76 mm; SD = 0.17; n = 18.
Subfacies 6-D. *Nummulites–Orbitolites* wackestone, locally packstone *Nummulites cuvillieri* and *Nummulites* spp. (3%); nummulithoclastic debris (2%); soritids, including *Orbitolites* (intact: 5%; broken 2%); *Alveolina* fragments (2%); micrite (55%); dolomite (10%); minor components include miliolids, textulariids, echinoids, ostracods, and dasycladacean algae. Fig. 7H.	Indistinctly bedded on a meter scale. Commonly bioturbated. Outcrop study (the area marked "3" in Fig. 3) suggests that this facies is laterally continuous for at least 2 km. Intact echinoids are common, & are the dominant macrofauna in this facies. Biofabrics: "isolated chaotic," "tangential circular," & "planar tangential" Fig. 10E, F.	**A:B ratio**: Locally only A-forms are present; where B-forms occur ratio is 12:1 **Density**: A-form av. = 0.91/cm^2; B-form av. = 0.04/cm^2. **Test size/shape**: A-form D/T av. = 1.57 mm; SD = 0.11; n = 5.
(*Facies 6 is subdivided on the basis of LBF content, texture & biofabric*).		

Abbreviations: n'clastic—nummulithoclastic; LBF—larger benthic foraminifera; SBF—smaller benthic foraminifera; sub-a—subangular; sub-r—subrounded; SCS—swaly cross stratification; CRA—coralline red algae; SQU—Sultan Qaboos University; abbreviations in "biometrics" column: D—diameter; T—thickness; av.— average; SD—standard deviation; n—number of tests measured.

seagrass beds and other marine vegetation-stabilized substrates by Perry 1999) on the tests of larger foraminifera.

Peloids in this facies appear to be highly abraded fragments of articulated CRA and totally-micritized ?milioline foraminifera, although numerous (probable) fecal pellets were also identified, based on their rod- or ellipsoid-like shape, and also on their aggregate nature (cf. Pusey 1975). Occasional centimeter-scale linear accumulations of these (probable) fecal pellets in Facies 2 reinforce the interpretation that this facies was deposited under seagrass cover, because similar features have been noted in modern seagrass beds (Enos 1977), the product of annelid worms following seagrass roots, eating the organic material and depositing fecal pellets in the tunnel created. The presence of annelids may also, in part, account for the poorly defined bedding typical of this facies, because Pusey (1975) noted that annelids in *Thalassia* beds of the Belize shelf are largely responsible for the destruction of bedding. The nodular bedding may also be a consequence of physical modification by the rhizomes and roots of seagrasses, which can disturb sediment up to 2 meters below the sediment–water interface (Enos 1977; Wanless et al. 1995).

The benthic foraminifera in Facies 2 include typical protected or partly restricted shallow marine forms such as miliolids, textulariids, and

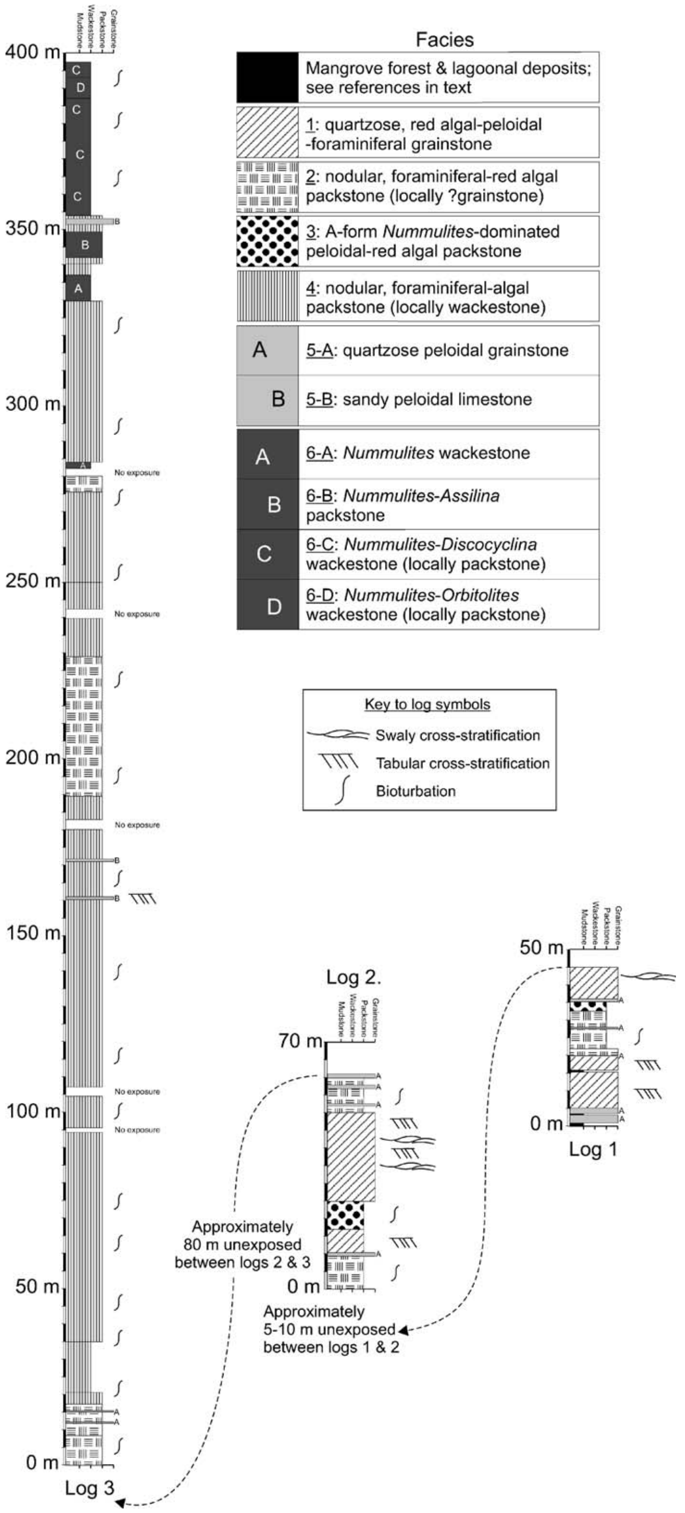


FIG. 5.—Logs of the Seeb Fm. at Al Khod (see Fig. 3 for log locations) showing an overall transgressive trend, passing up from nearshore facies at the base (dominated by high-energy shoreface or lower foreshore grainstones, and shallow subtidal seagrass beds), to a thick association of lagoonal sediment, overlain by shoals composed of larger nummulitid benthic foraminifera.

rotaliids. The presence of soritids (such as *Orbitolites*) and peneroplids, and (probable) encrusting forms such as *Eorupertia* sp. and the discorbid *Fabiania* sp. also indicates that deposition was influenced by vegetation cover, because living soritids and peneroplids are commonly (although not exclusively) found on seagrasses (e.g., Brasier 1975a; Hottinger 1997), and whilst encrusting foraminifera are present in many shallow marine environments, Davies (1970) noted that they reach their greatest abundance in sediment associated with seagrasses. However, this also implies that the larger foraminifera *Alveolina* and *Nummulites* in this facies are allochthonous, because neither have previously been identified as seagrass dwellers (although Eva 1980 observed that Recent alveolinids in the Caribbean live on sandy substrates adjacent to seagrass beds).

The apparently low-energy environmental setting concluded for this mud-rich facies may also be a consequence of deposition under seagrass cover, because studies of modern seagrass beds (e.g., Davies 1970; Scoffin 1970) show that muddy, apparently low-energy facies may form even in high-energy settings, a result of the current-baffling action of seagrass leaves.

To summarize, Facies 2 represents deposition in a shallow marine, low-energy environment. Although many types of fauna and flora present in this facies are or were not restricted to seagrass environments, growth forms of crustose CRA, and the presence of "constructive" micrite envelopes, as well as an abundance of encrusting foraminifera and forms commonly associated with seagrasses, strongly suggest the presence of seagrass. Bio-disturbance caused by seagrass roots and associated infaunal burrowers may also help explain the poorly developed, nodular bedding in this mud-rich facies.

Facies 3. A-Form Nummulites*-Dominated Peloidal–Red Algal Packstone*

The decimeter-scale beds of Facies 3 are interbedded with Facies 1, 2, and 5-A, near the base of the measured section (Fig. 5). Deposition in a low-energy regime is indicated by the presence of carbonate mud, common burrows, and biogenically produced biofabrics (Table 1), although occasional "tangential circular" and "planar tangential" biofabrics may represent tubular tempestites (see Fig. 4) and may indicate periodic storm influence.

The *Nummulites* assemblage in this facies is overwhelmingly dominated by A-forms of a single species: *N. praediscorbinus* (Beavington-Penney 2002). Taphonomic study of the tests suggests that they are largely autochthonous. Their ovate, robust shape (average D/T ratio 1.87; see Table 1) suggests deposition in shallow water, because studies of living LBF have indicated that such robust, ovate tests are produced by foraminifera that live in very shallow water, as a protection against photoinhibition of symbiotic algae within the test in bright sunlight, and/or test damage in turbulent water (e.g., Larsen 1976; ter Kuile and Erez 1984; Hallock and Glenn 1986). A-form-dominated LBF communities can be the result of apogamic schizogony (repetitive asexual reproduction resulting in successive generations of megalospheric schizonts, e.g., Dettmering et al. 1998), possibly reflecting increased nutrient flux, or rapid population increase in marginal habitats, after mortality events or during colonization of new areas (Lipps 1982; Harney et al. 1998). Interestingly, Brasier (1975b) observed that nutrient levels within and adjacent to seagrass beds are higher than in surrounding environments, and so the close proximity of this facies to the (likely) seagrasses of Facies 2 suggests a possible mechanism (i.e., increased nutrient flux) for the origin of this population of A-form *Nummulites*, although it is not possible to confidently identify the paleoenvironmental significance of the dominance of A-form *Nummulites* in Facies 3, due to the possible alternative interpretations.

Other bioclasts in this facies are indicative of deposition within a shallow marine environment and are largely identical to the assemblage present in the seagrass-influenced Facies 2 (see Table 1). In particular, the abundance of foliose fragments of crustose CRA (including hooked forms; Fig. 6F) again strongly suggests that this facies was deposited in a vegetated area. However, the presence of abundant *Nummulites* in this facies suggests perhaps either a close proximity to seagrass or deposition in a sparsely or seasonally vegetated area rather than under dense seagrass cover. Several other processes may be responsible for the presence of encrusting epiphytes in this facies: West and Larkum (1979) showed that the high turnover rate of the leaves of the seagrass *Posidonia australis* in eastern Australia results in the transport of significant quantities of leaf litter (and calcareous epiphytes) into adjacent areas, whilst Gostin et al. (1984) noted that storm-induced winnowing of seagrass beds has a similar effect.

To summarize, this facies represents an A-form *Nummulites* population living in a shallow marine, low-energy environment, in close proximity to the seagrass "banks" of Facies 2, or possibly on a patchily or seasonally vegetated substrate. It may perhaps be speculated that increased nutrient flux related to the close proximity of seagrasses (Facies 2) may explain the presence of this shallow water A-form *Nummulites* population.

Facies 4. Nodular Foraminiferal–Algal Packstone (Locally Wackestone)

Facies 4 dominates the logged succession (with a total thickness of 250 m) and is interbedded with Facies 2, 5-B, 6-A, and 6-B (Fig. 5). Compositionally it is broadly similar to Facies 2 but is differentiated on bioclastic and biofabric evidence of deposition under less dense marine vegetation cover. Deposition in a low-water-energy environment is indicated by the local abundance of micrite. The presence of rare, thin (up to 1 cm) sheets of gypsum along some bedding planes, and also local dolomite, but with an absence of sedimentary features commonly associated with gypsum in such environments, indicates that such features may be a later diagenetic feature.

Observed biofabrics in this facies, including "isolated chaotic" and "subhorizontal stacking," suggest that burrowing organisms were common (Fig. 4). Occasional dense meshworks of horizontal burrows exposed in hypichnial relief on basal bedding planes indicate that intense biological reworking has thoroughly modified this facies (Fig. 9C). Extensive transformation of original fabrics is also indicated by the lack of well-defined bedding and the highly nodular appearance of this facies (Fig. 9A, B), and also by a general lack of distinct burrows, which, as observed by Tedesco and Wanless (1991), is a feature of the thoroughly "bio-retextured" sediments of Florida Bay and the Caicos platform. However, infaunal spatangoid echinoids occasionally preserved *in situ* in horizontal burrows indicate that these were at least partly responsible for the bio-retexturing of Facies 4. Living relatives of these echinoids are common in unconsolidated sandy sediments in mid-shelf and back-reef environments, where they destroy sedimentary structures as they plough through the sediment (Kier and Grant 1965; A. Smith, personal communication 2001). They cannot cope with extensive seagrass roots or green algal holdfast filaments, so they are restricted to largely unvegetated areas.

Biofabrics indicative of periodic high-energy events are also present, including "tangential circular" and "planar tangential," which suggest the storm-infilling of open burrow networks (Fig. 4) (although spatangoid echinoids may produce similar biofabrics, e.g., Bromley and Asgaard 1975; Kanazawa 1995). Occasional "depression fill" biofabrics also suggest high-energy scouring events, although such features may result from seafloor disturbance by feeding predators such as rays (cf. Hall 1994).

Bioclasts in this facies indicate deposition in shallow marine waters. CRA are volumetrically the most significant contributors and include both articulated and foliose crustose forms (including hooked forms). Like the dasycladacean and halimedacean green algae, which are also common, they suggest deposition in a shallow marine (< 30 m) environment. The presence of hooked CRA suggests the influence of seagrasses, although the presence of infaunal echinoids that are restricted to sparsely vegetated or nonvegetated areas suggests that seagrass cover was probably very limited (or that the sediments are time averaged). Therefore, many of the (probable) seagrass epiphytes in this facies (which also includes encrusting foraminifera, soritids such as *Orbitolites*, and peneroplids) may be the result of the transport of seagrass leaves into nonvegetated areas, or of the storm-winnowing of adjacent seagrass beds. Crustose CRA are also present as rhodoliths (Fig. 7B), including concentrically laminated forms and also irregular forms encrusted on one side. Rhodoliths occur in a wide variety of settings, including back-reef, reef flat and channel, fore-reef, and also in deeper water down to 250 m (Bosence 1983, and references therein). The presence of forms encrusted mainly on one side suggests that energy levels either were locally not high enough to turn some rhodoliths or were generally low, and concentrically laminated forms are a consequence of bio-induced movement, through the burrowing and/or feeding activities of organisms such as fish and echinoids (e.g., Bosellini and Ginsburg 1971; Bosence 1983; Prager and Ginsburg 1989).

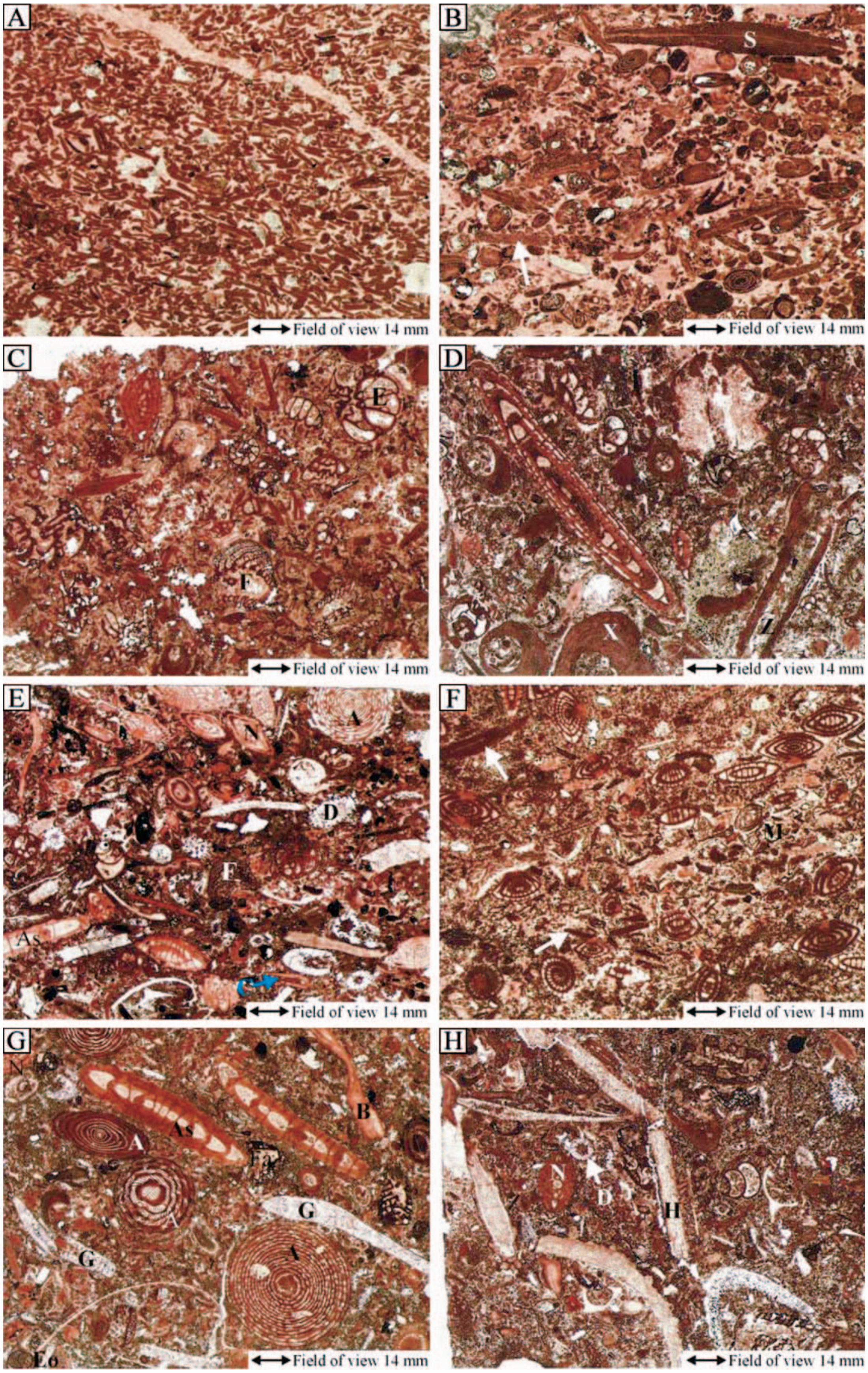
The presence of common peloids, plus miliolid, textulariid, and rotaliid foraminifera, is suggestive of shallow, protected or partly restricted conditions. The occurrence of symbiont-bearing foraminifera such as robust A-form *Nummulites* and *Assilina*, and locally very abundant elongate, fusiform *Alveolina* (up to 60 mm long), reinforces the interpretation of deposition in a shallow marine, unvegetated environment. Brasier (1984) suggested that the tendency towards large, elongate tests in *Alveolina* is a strategy designed to increase surface area and is consistent with the occupation of relatively deep (i.e., mesophotic) waters.

Coral fragments occur in low numbers throughout this facies. They are occasionally encrusted on one surface by foliose crustose CRA, and they may indicate the presence of nearby patch reefs. Elongate clusters of intertwined calcareous teredinid tubes, up to 2 m in length and 15 cm in thickness, occur rarely in Facies 4. Teredinids are a highly specialized family of marine wood-boring bivalves, and fossilized accumulations of intertwined teredinid tubes have previously been interpreted as having been infesting driftwood that sank to the seabed, and they are considered indicative of ancient mangroves (Savazzi 1999; Huggett et al. 2000). Therefore the presence of teredinid accumulations in this facies suggests that the contemporary shoreline was lined by mangroves, as it was during deposition of the underlying Rusayl Fm.

In summary, deposition of this facies is interpreted to have occurred in a low-energy, shallow marine (< 30 m deep), protected (but not restricted), lagoonal environment, which was sparsely vegetated by seagrasses, articulated CRA, and calcareous green algae, possibly close to a mangrove-fringed shoreline. Normal salinities (i.e., a connection to the open ocean) are suggested by the presence of (possible) patch reefs and the abundant, diverse biota. Sediments were thoroughly bio-retextured by the activities of burrowing echinoids and other organisms. Periodic high-energy events are suggested by "tubular tempestites," scours, and also by concentrically laminated rhodoliths; however, alternative, lower-energy explanations for all of these high-energy features cannot be discounted.

Subfacies 5-A. Quartzose Peloidal Grainstone

The decimeter- to meter-scale, quartzose peloidal grainstones of Subfacies 5-A are interbedded with Facies 1, 2, 3, and also the Rusayl Fm. (Fig. 5). Several lines of evidence suggest that they were deposited in a shallow marine, nearshore environment. These include the presence of abundant (average 11.6%) angular to subangular, fine-grained and well-sorted quartz grains, and also an abundant assemblage of shallow marine (commonly micritized) foraminifera (the latter reminiscent of the assemblage in the seagrass-influenced sediments of Facies 2, suggesting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Field of view 14 mm

that it was, at least in part, sourced from that environment). The close proximity of marine vegetation is also suggested by the presence of locally abundant foliose and tubular (sheath-like) crustose CRA (see Fig. 7D), which is also similar to that found in Facies 2. The occurrence of articulated CRA also indicates deposition in the shallow marine realm, whilst a high-energy regime is suggested by the degree of abrasion noted on both foraminiferal tests and the disarticulated intergenicula of articulated CRA, and also by the degree of sorting exhibited by the quartz grains.

Although no evidence of subaerial exposure was observed in the field (e.g., calcretes, rhizocretions, or evaporite mineral growth), the occasional presence of irregular fractures, infilled by nonferroan calcite spar, in this facies, which often give the rock a brecciated appearance (Beavington-Penney 2002), may suggest episodic exposure. However, the general absence of vadose cements in this facies appears to suggest that such exposure events were rare.

Possible analogs for such mixed siliciclastic–carbonate deposits have been documented from recent intertidal zones in Shark Bay, western Australia (Davies 1970; Read 1974) and northern Spencer Gulf, southern Australia (Gostin et al. 1984). They generally occur as linear sand ribbons, several hundreds of meters long and up to several decimeters in thickness. They are moved by longshore drift, are locally trapped by the root and pneumatophore networks of mangrove communities, and may terminate at the margins of tidal channels. These sand ribbons are often associated with seagrasses, and they may locally prograde from the shore and bury seagrass beds. In addition, they may themselves be colonized by seagrasses. This association may explain the occurrence of locally dense accumulations of foliose (hook-shaped) and tubular crustose CRA in Subfacies 5-A, identified as probable seagrass encrusters.

Subfacies 5-B. Sandy Peloidal Limestone

The decimeter- to meter scale, sandy peloidal limestones of Subfacies 5-B are interbedded (rarely) with Facies 4 (Fig. 5). They share many similarities with Subfacies 5-A, although differences in sedimentary structures, allochem content, and associated facies suggest that this facies was deposited in slightly deeper water than Facies 5-A, away from the shoreline and within the protected environment inferred from Facies 2, 3, and 4.

Whilst some evidence exists for periodic (rare) subaerial exposure of Subfacies 5-A, no such evidence was observed within 5-B, suggesting deposition in the subtidal realm. The erosional contact at the base of this facies and the presence of tabular cross-bedding suggest deposition during high-energy (?storm) events. The lags of LBF tests (dominantly large *Alveolina*) that overlie the basal erosion surface may be the result of rapid settling from suspension during the waning phase of such events. Several authors have described similar lags of alveolinid tests that formed due to differential settling velocities (e.g., Severin and Lipps 1989). Davies (1970) noted accumulations of *Alveolinella* sp. in recent ebb-tidal delta lobes at the seaward ends of tidal channels in eastern Shark Bay, which he interpreted as lag deposits transported from the outer intertidal zone. Davies (1970) also noted that the delta lobes contained a larger proportion of angular to subangular quartz than was to be found in the intertidal sand ribbons (i.e., the suggested modern equivalent of Subfacies 5-A); as such, these ebb-tidal delta lobes may represent a possible analog for Subfacies 5-B, which, in addition to *Alveolina* lags, also has a higher quartz content than Subfacies 5-A (average 33.3% in 5-B, versus average 11.6% in 5-A).

Subfacies 6-A. Nummulites Wackestone

The *Nummulites* wackestones of Facies 6-A are interbedded with Facies 4 (Fig. 5). High micrite content (locally reaching 50%) implies a low-energy environment of deposition. Biogenically produced biofabrics (i.e., "isolated chaotic;" see Fig. 4), the presence of common horizontal burrows and irregular echinoids, and the nodular, poorly defined bedding also indicate a low-energy, thoroughly bioturbated environment, although occasional contact imbrication and tangential circular biofabrics suggest the periodic influence of currents, and the storm infilling of open burrow networks as tubular tempestites (Tedesco and Wanless 1991, 1995; see Fig. 4).

The highly "robust" tests of the intact (?*in situ*) A-form-dominated *Nummulites* population (average D/T ratio 1.65) in this low-energy environment may reflect a defense mechanism designed to protect the symbiotic algae within the test against photoinhibition in bright sunlight (as suggested by studies of living LBF, e.g., Larsen 1976; Hallock 1979; Hallock and Hansen 1979), which suggests that these foraminifera were living in shallow, euphotic waters.

The presence of marine vegetation during deposition is suggested by "constructive" micrite envelopes (cf. Perry 1999) developed on a small percentage of *Nummulites* tests (see Fig. 7E). However, the presence of common infaunal echinoid burrows suggests that such vegetation would have been sparse, or only locally abundant (or reflects time averaging of the sediment). Deposition in a shallow, protected, seagrass-influenced area is also indicated by many other bioclasts in this facies, including micritic peloids, soritids (including *Orbitolites*), alveolinids, miliolids, textulariids, (probable) encrusting foraminifera, articulated and foliose CRA (including hook-shaped forms of the latter), and dasycladacean green algae.

The abundance of *Nummulites* fragments and nummulithoclastic debris in this low-energy facies is unlikely to reflect *in situ* fragmentation by abrasion, but rather it seems more likely that such damage was the result of predation by organisms such as echinoids, gastropods, or fish (cf. Beavington-Penney 2004). The presence of macroborings (up to 0.4 mm in diameter) observed on LBF tests in this facies (Beavington-Penney 2002) may attest to the activities of predators. Alternatively, some or all

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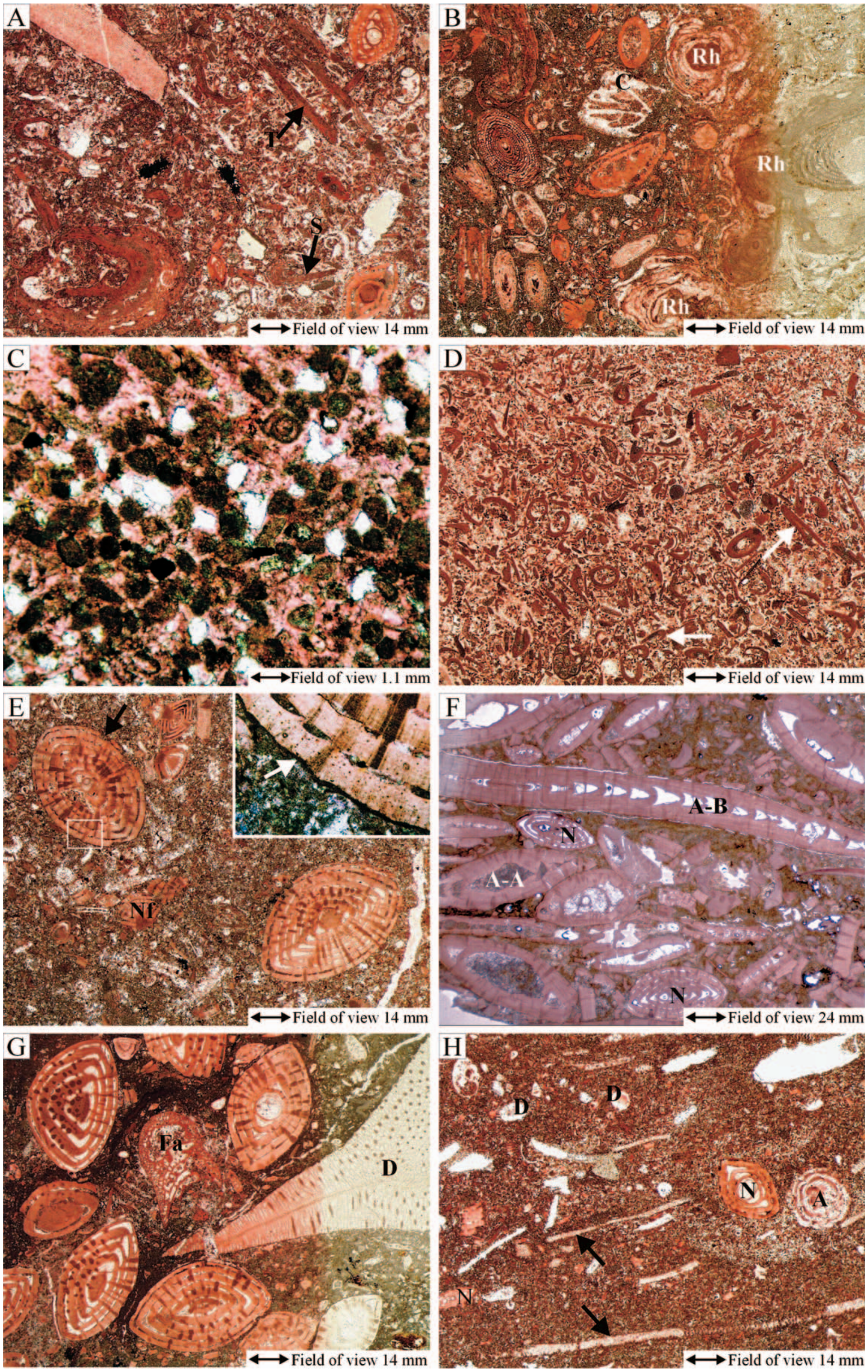
FIG. 6.— Photomicrographs (of thin sections stained with Alizarin Red S and potassium ferricyanide. **A)** Facies 1, quartzose, red algal–peloidal–foraminiferal grainstone. Photomicrograph of (probable) swaly cross-stratified unit. Note poorly sorted, angular quartz. The abundant skeletal debris (composed largely of coralline red algae, micritized grains, and foraminifera) displays a well-developed preferential orientation. **B)** Facies 1, quartzose, red algal–peloidal–foraminiferal grainstone. Photomicrograph of cross-stratified unit, composed of abundant foraminifera, including *Somalina* sp. (S), fragments of soritids (arrowed), plus common miliolids and ?juvenile *Alveolina*. **C)** Facies 2, nodular foraminiferal–red algal packstone. Note abundant encrusting(?) foraminifera, including *Fabiania* sp. (F) and ?*Eorupertia* sp. (E). **D)** Facies 2, nodular foraminiferal–red algal packstone. Note common tubular crustose coralline red algae, shown in cross sections parallel to the long axis of tubes (Z) and perpendicular to that axis (X), plus *Nummulites* and fragments of the large encrusting foraminifera *Eorupertia*. **E)** Facies 2, nodular foraminiferal–red algal packstone. Note dasycladacean green algae (D), A-form *Nummulites* (N), *Assilina* (As), *Alveolina* (A), *Fabiania* (F), and foliose coralline red algae, including hooked forms (C), indicative of growth on the leaves of seagrasses or other marine vegetation. **F)** Facies 3, A-form *Nummulites*–dominated, peloidal–red algal packstone. Note foliose crustose coralline algae, including hook-shaped fragments (arrowed), and miliolids (M). **G)** Facies 4, nodular foraminiferal–algal packstone, with *Assilina* (As), *Nummulites* (N), *Alveolina* (A), calcareous green algae (G), bivalve (?oyster) fragment (B), and ?encrusting foraminifera cf. *Fabiania* (Fa) and cf. *Eorupertia* (Eo). **H)** Facies 4, nodular foraminiferal–algal packstone, with *Nummulites* (N) and common calcareous green algae, including halimedaceans (H), replaced by nonferroan microspar and finely crystalline spar, and still exhibiting fine-scale internal structures, and dasycladaceans (D), replaced by coarser calcite spar.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of the fragments could be allochthonous and may have originated from the higher-energy Subfacies 6-B. Transport of bioclasts from Subfacies 6-B is also indicated by the presence of occasional *Assilina* and *Discocyclina* fragments, as well as occasional intact B-form *Assilina*, all of which are common in that facies.

To summarize, Subfacies 6-A represents deposition of a largely *in situ* A-form-dominated *Nummulites* community in a shallow, well-lit, low-energy, protected environment, which may have been sparsely or patchily covered by seagrasses and green algae. Periodic high-energy (?storm) events are indicated by the presence of localized contact imbrication biofabrics and possible tubular tempestites, as well as by the occurrence of (probable) allochthonous fragments that may have originated from higher-energy subfacies within Facies 6.

Subfacies 6-B. Nummulites–Assilina Packstone (Locally Grainstone)

The *Nummulites–Assilina* packstones (locally grainstones) of this subfacies are interbedded with Facies 4 (Fig. 5). Outcrop study (in the area marked "3" in Fig. 3) indicates that these facies grade into each other over a few meters along strike, with Subfacies 6-B forming sheetlike bodies, up to 7 m thick and several hundred meters long (i.e., they form biostromal reef mounds, similar to those described by Racey 1994, 1995, 2001, from the Seeb Fm. type section at Wadi Rusayl). Larger foraminiferal biofabrics in this facies, including contact imbrication, linear accumulation, and chaotic stacking, suggest deposition in a high-energy area influenced by currents and waves (see Fig. 4), although the dominance of packstone textures (with up to 35% micrite) indicates that these currents were either too weak to winnow away much of the carbonate mud or only infrequently affected an area where sediment was accumulating in less turbulent conditions. Periodic reworking is also indicated by occasional non-bedding-parallel geopetal micrite fills within LBF chambers. Biogenically produced biofabrics (see Table 1) are not inconsistent with deposition in such an environment, because burrowing organisms such as shrimps have been reported from all but the very highest-energy areas of modern bioclastic and oolitic sand shoals (Tedesco and Wanless 1991). High-energy conditions are also indicated by the abundance of broken LBF debris, including fragments of *Nummulites* and *Assilina*, and the robust, ovate tests of intact *Nummulites* (average D/T ratio 1.75).

Large, flat *Assilina* have previously been interpreted as forms that lived in deep, oligophotic water (e.g., Racey 1994; Luterbacher 1998; Geel 2000), and also in much shallower, open marine, high-energy settings (e.g., Ghose 1977; Gilham and Bristow 1998). Although the genus *Assilina* is now extinct, living nummulitids with similar large, flat tests (e.g., *Cycloclypeus carpenteri* and *Heterocyclina tuberculata*) have been collected from water depths up to 150 m (e.g., Reiss and Hottinger 1984; Hohenegger 2000), although *Assilina* examined during this study generally exhibit far thicker test walls than those of their more fragile, extant relatives. It is suggested that the association within this facies of large, thick-tested, often fragmented *Assilina* with an A-form-dominated community of robust, often abraded *Nummulites*, combined with biofabrics indicative of hydrodynamic reworking, favors comparison with the shallower-water occurrences noted above.

Bioclasts including soritids, miliolids, textulariids, (probable) encrusting foraminifera, coral fragments, dasycladacean algae, and oysters also indicate a shallow marine, protected environment of deposition. It is considered likely that the locally abundant *Discocyclina* in this facies were sourced from the adjacent Subfacies 6-C.

To summarize, biofabrics and textures indicative of wave and current reworking within this facies, combined with the fragmented state of many LBF tests, and also the biostromal reef-mound geometry exhibited by these accumulations, suggest that this facies represents a parautochthonous (partly allochthonous?) "shoal," possibly formed close to fair-weather wave base (FWWB) by waves and ?storm currents that heaped *in situ* LBF tests, as well as bioclasts sourced from adjacent facies, into low-relief mounds.

Subfacies 6-C. Nummulites–Discocyclina Wackestone–Packstone

Subfacies 6-C is interbedded with Facies 4 and 6-D (Fig. 5). Deposition in a low-energy regime is suggested by the abundance of micrite (average 48%), the dominance of biogenically produced biofabrics such as subhorizontal stacking and isolated chaotic (see Fig. 4), and also by large ?backfilled (?crustacean) burrows whose margins are defined by accumulations of both intact and fragmented larger foraminifera (see Fig. 10C). Local contact imbrication of tests suggests the periodic influence of currents, and tangential circular and planar tangential biofabrics within some burrows suggest that storms may have influenced the seafloor during deposition (see Fig. 4).

Common in this facies are large *Discocyclina*. Previous studies have interpreted *Discocyclina* as having lived in a broad spectrum of environments in the photic zone, including shallow fore-reef and back-reef environments (e.g., Henson 1950; Racz 1979; Anketell and Mriheel 2000) and deeper, outer-ramp environments (e.g., Racey 1994; Gilham and Bristow 1998). Other authors have noted an environmental control on test morphology, with *Discocyclina* in very shallow photic-zone settings having small, robust tests, whilst those living in lower-light, deeper settings have large flattened tests (e.g., Ghose 1977; Loucks et al. 1998; Sinclair et al. 1998; Geel 2000). No consensus has been reached regarding the mode of life of these extinct forms (e.g., Bieda 1963; Fermont 1982; Less 1987), although Ferràndez-Cañadell 1989 (quoted in Ferràndez-Cañadell and Serra-Kiel 1992) suggested that saddle-shaped forms (typical of Subfacies 6-C; see Fig. 10D) are an adaptation related to algal symbiosis, allowing the test to lie in any position and always have a zone directly exposed to sunlight. The large size and saddle-like morphology of *Discocyclina* in this facies may therefore indicate

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FIG. 7.—Photomicrographs (of thin sections stained with Alizarin Red S and potassium ferricyanide, unless otherwise stated). **A)** Facies 4, nodular foraminiferal–algal packstone, with crustose coralline red algae (C), including foliose ?tubular (T) and hook-shaped (S) forms. **B)** Facies 4, nodular foraminiferal–algal packstone. Note common rhodoliths (Rh), plus ?coral fragments (C). The core of the rhodolith in the right-hand (unstained) side of the photomicrograph is an alveolinid. **C)** Subfacies 5-A, quartzose peloidal grainstone. Note well-sorted, angular, fine-grained quartz and subrounded micritic grains. **D)** Subfacies 5-A, quartzose peloidal grainstone. Locally abundant in this facies are accumulations of crustose coralline red algae, as both circular (?tubular) and foliose forms. Foliose forms commonly exhibit one flat surface, and may have a hooked morphology (e.g., where arrowed). **E)** Facies 6-A, *Nummulites* wackestone. Note that several species of A-form *Nummulites* occur. Fragmented *Nummulites* are present (e.g., Nf), and many tests show evidence of bioerosion or abrasion (e.g., where arrowed). The "robust" *Nummulites* test in the top left of the photomicrograph has a "constructive" micrite envelope, indicative of deposition in the presence of seagrass or other marine vegetation (cf. Perry 1999). The boxed area is enlarged in the inset. **F)** Facies 6-B, *Nummulites–Assilina* packstone, with A-form *Assilina* (A-A), B-form *Assilina* (A-B), and *Nummulites* (N). Note common *Nummulites* and *Assilina* debris. **G)** Facies 6-C, *Nummulites–Discocyclina* wackestone. Note common A-form *Nummulites*, plus large *Discocyclina* (D) and ?encrusting foraminifera cf. *Fabiania* (Fa). Micritic matrix commonly displays patchy "cryptofabric," possibly related to sponge growth. Partially stained thin section. **H)** Facies 6-D, *Nummulites–Orbitolites* wackestone. Note A-form *Nummulites* (N; two species present), *Alveolina* (A), plus soritid foraminifera (including *Orbitolites* sp.), e.g., where arrowed. Also present are probable dasycladacean algae (now replaced by calcite spar; D).

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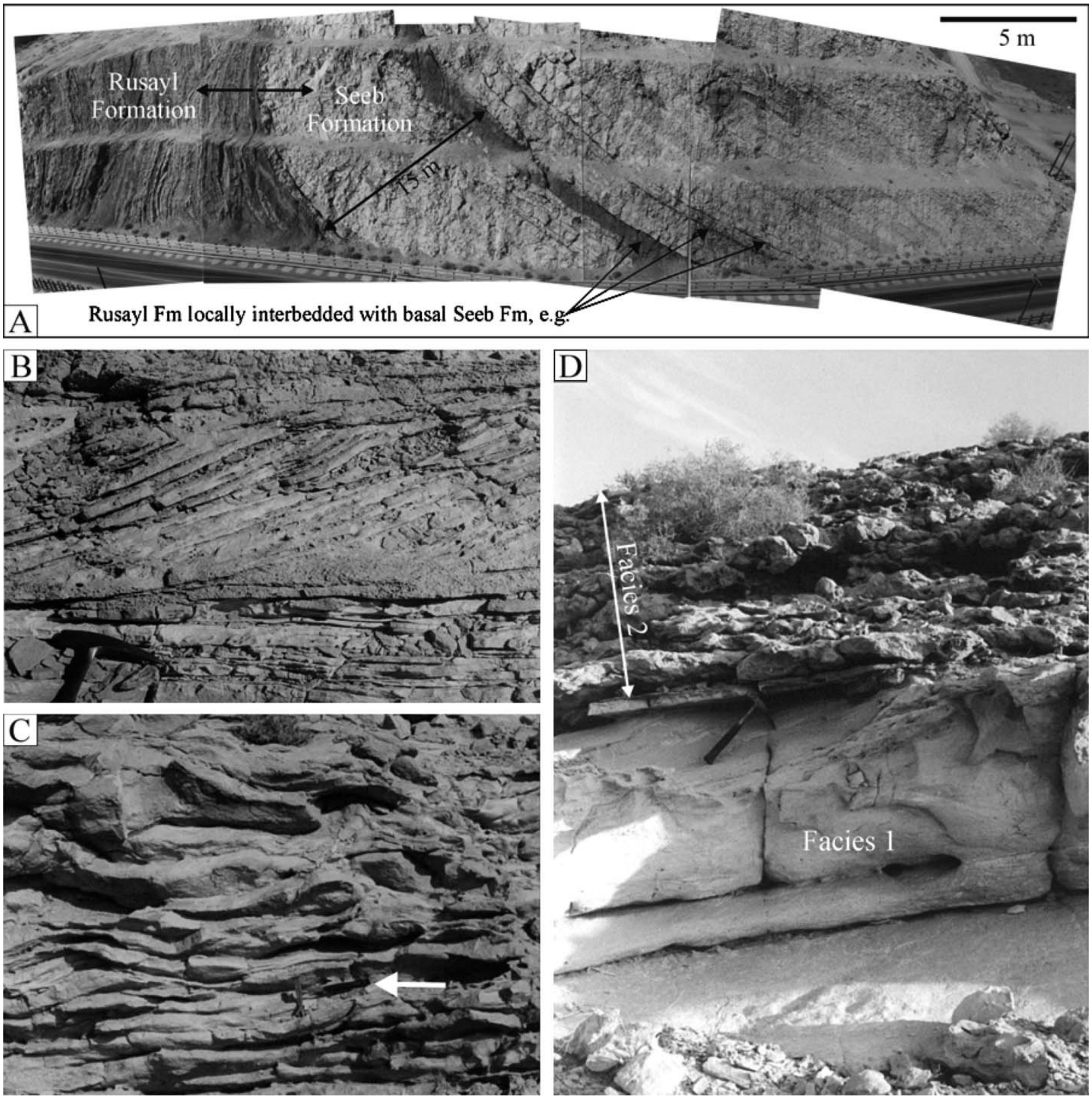


FIG. 8.—Macro characteristics of Facies 1 and 2 at Al Khod. **A)** Photomontage of the Rusayl Fm./Seeb Fm. transition at Al Khod road cut (see Fig. 3 for location). **B)** Planar cross-stratification in Facies 1. Hammer head is 19 cm long. **C)** Possible swaly cross-stratification in Facies 1. Hammer (arrowed) is 33 cm long. **D)** Nodular Facies 2, overlying Facies 1. Hammer is 33 cm long.

deposition in somewhat deeper, less well-lit water than that inferred for other facies in this association, although their co-occurrence with dasycladacean algae and large, robust *Nummulites* (average D/T ratio 1.76) makes it appear unlikely that they were deposited in significantly deeper water. This is reinforced by the presence of large soritids, alveolinids, miliolids, textulariids, small rotaliids, locally abundant coral fragments, as well as articulated and foliose crustose CRA, and also (probable) encrusting foraminifera, which indicate a shallow marine environment that either had a sparse seagrass cover or was in close proximity to vegetated areas.

Subfacies 6-D. Nummulites–Orbitolites Wackestone, Locally Packstone

Subfacies 6-D is interbedded with Subfacies 6-C (Fig. 5). A low-energy environment of deposition is indicated by the high lime mud content of this facies (up to 55%) and also by isolated chaotic and subhorizontal

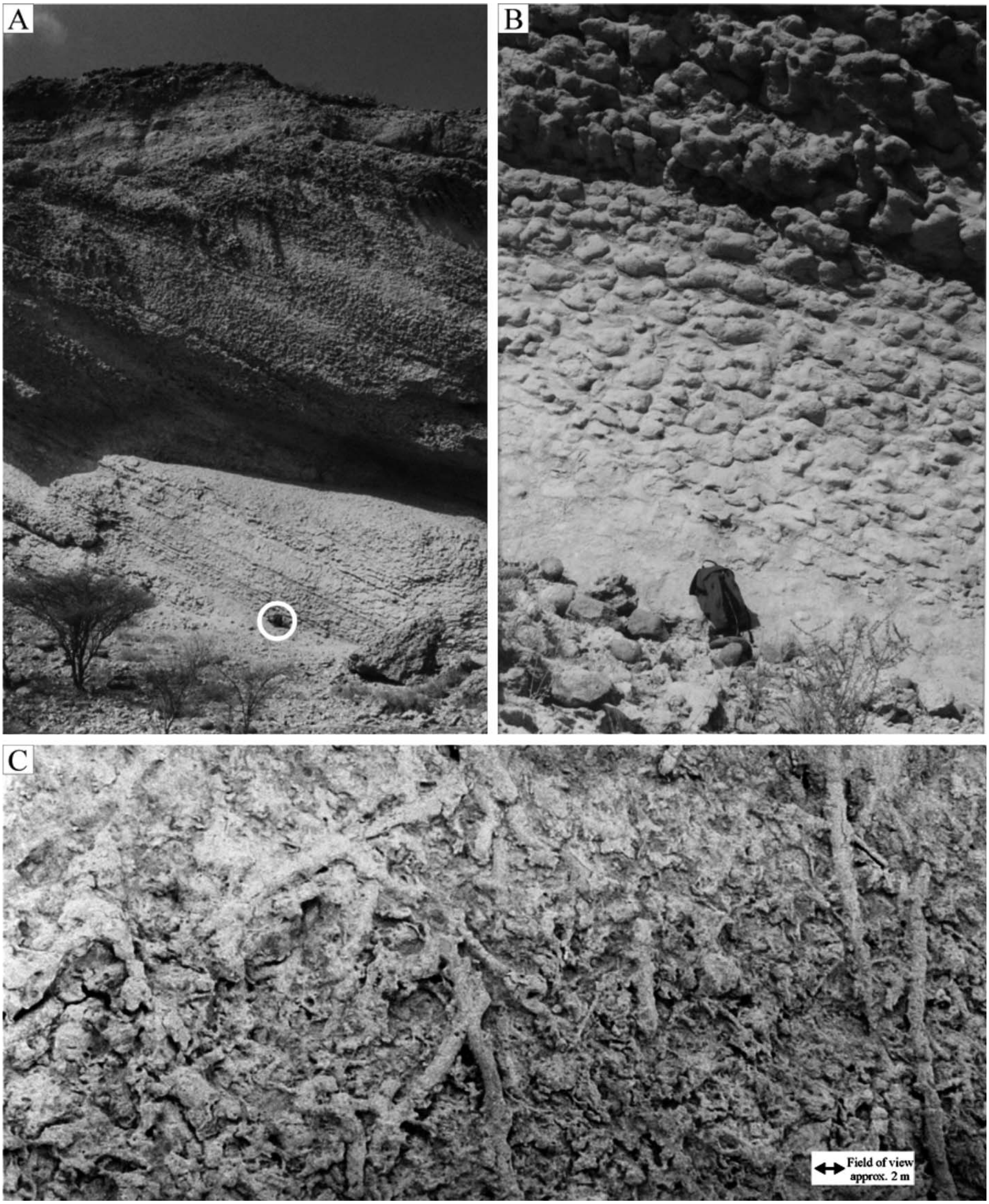


FIG. 9.—Macro characteristics of Facies 4 at Al Khod. **A)** Thick accumulation of Facies 4 in Wadi Al Khod. Note nodular appearance and lack of well-defined bedding—a common feature of thoroughly bio-retextured sediment. Rucksack (circled) is approximately 40 cm high. **B)** Nodular bedding of Facies 4. **C)** Hypichnial (base of casting bed) view of horizontal burrows in Facies 4. Such dense burrow meshworks strongly suggest that intense biological reworking has thoroughly modified this facies.

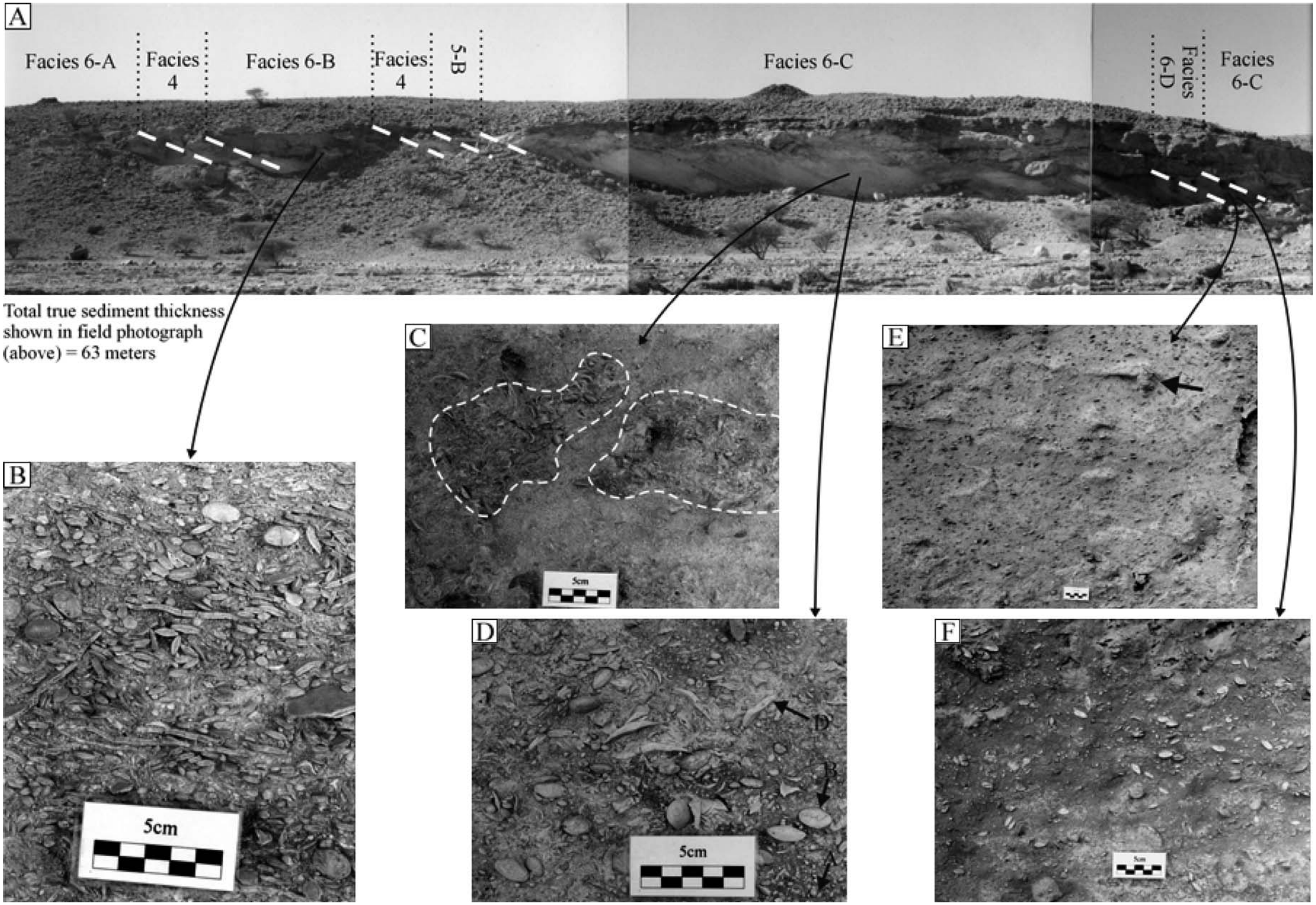


FIG. 10.—Macro characteristics of Facies 6 at Al Khod. **A)** Overview of Facies 6 outcrops in Wadi Al Khod. Seeb Fm. sediments are partly obscured by Pliocene–Quaternary alluvial gravel, derived largely from mantle and ophiolite outcrops to the south. **B)** Facies 6-B. *Nummulites–Assilina* packstone (locally grainstone). Abundant A- and B-form *Nummulites* and *Assilina*, exhibiting contact imbrication and chaotic stacking biofabrics, and representing a parautochthonous shoal that likely formed close to fair-weather wave base. **C, D)** Facies 6-C. *Nummulites–Discocyclina* wackestone (locally packstone). Tests are commonly clustered in large (?crustacean) burrows, e.g., where outlined by dashed white lines in Part C. Note A-form *Nummulites* (A), B-form *Nummulites* (B), and saddle-shaped *Discocyclina* (D), shown in Part D. **E, F)** Facies 6-D. *Nummulites–Orbitolites* wackestone. Tests are commonly clustered in burrows, e.g., where arrowed in Part E. *Nummulites* commonly exhibit an isolated chaotic biofabric, as shown in Part F.

biofabrics indicative of "biological bulldozing" and backfilling by infaunal organisms, although larger foraminifera clustered within burrows also display tangential circular and planar tangential biofabrics, which may indicate storm infilling of open burrow networks (see Fig. 4).

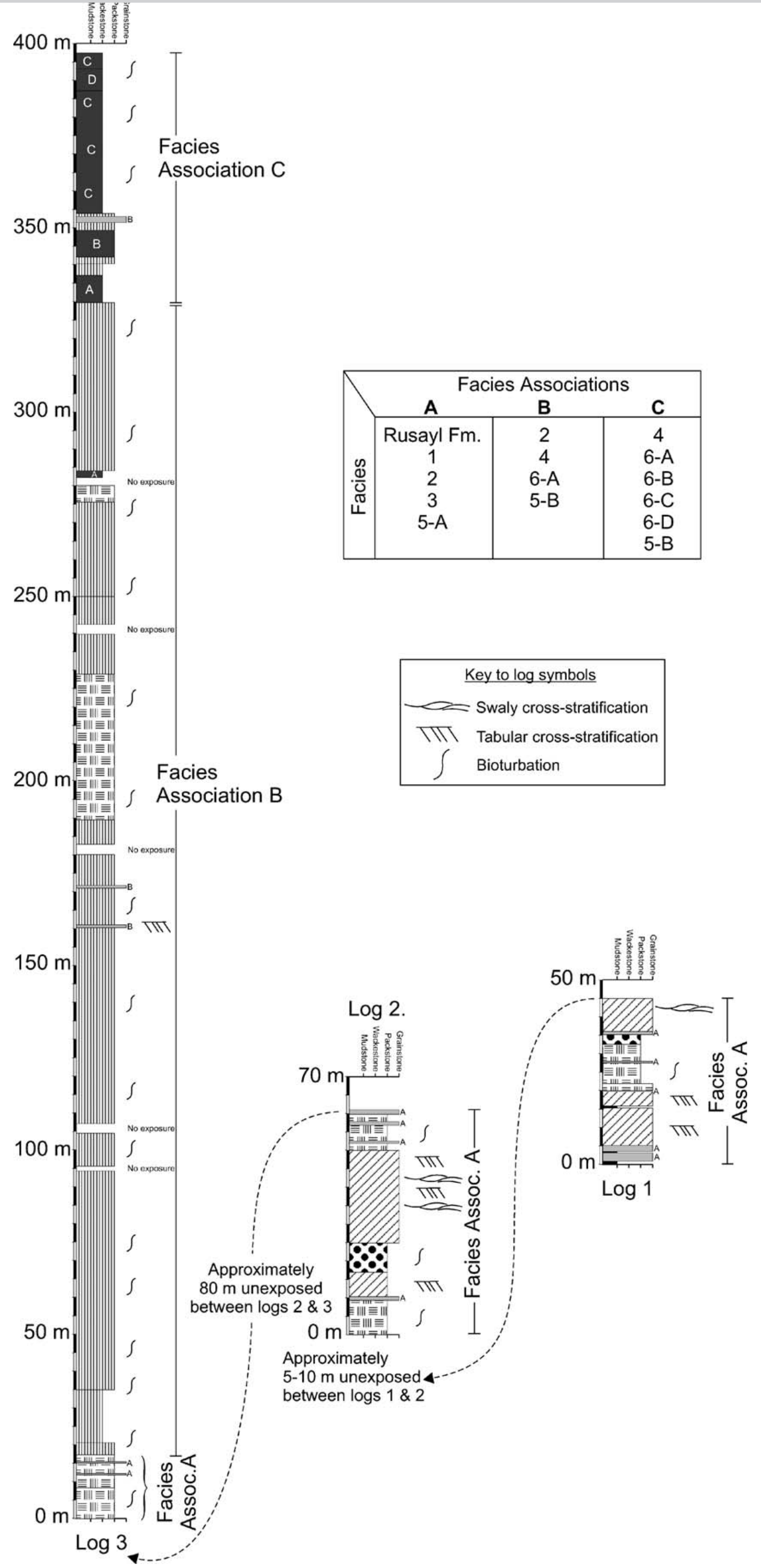
The association of robust A-form *Nummulites* and soritids (including *Orbitolites*) is suggestive of shallow, protected, ?vegetated environments. However, in view of its interbedded relationship with the fore-bank Subfacies 6-C, it should perhaps be noted that whilst living soritids are commonly described from shallow lagoonal environments (e.g., Murray 1994), several authors have noted their rare occurrence in deeper, more open water (e.g., Hohenegger et al. 1999; Hohenegger 2000; Langer and Hottinger 2000). However, the presence of rare dasycladacean algae, miliolids, and textulariids does seem to reinforce an interpretation of deposition in a shallow marine, protected environment. It appears possible that Subfacies 6-D represents a fall in sea level during deposition of 6-C. Alternatively, it may reflect the creation of protected or restricted conditions through the installation of an effective, more distal barrier (perhaps composed of Subfacies 6-B?).

FACIES ASSOCIATIONS, AND A DEPOSITIONAL MODEL FOR THE SEEB FORMATION AT AL KHOD

Seeb Fm. facies fall into three clearly distinguishable associations (Fig. 11), which are summarized below and integrated into an overall depositional model for the Seeb Fm. at Al Khod (Fig. 12). Facies Association A occurs in the basal part of the studied section, encompassing all the sediments in logs 1 and 2, and the lowermost 17 m of log 3 (see Fig. 11). It reflects the juxtaposition of several nearshore (low intertidal to shallow subtidal) environments, probably backed by mangrove swamp or forest deposits comparable to the Rusayl Fm. High-energy grainstones (Facies 1), composed of allochthonous, shallow-water bioclasts sourced, as least in part, from adjacent (shallow subtidal?) seagrass banks (Facies 2) were deposited on a storm-influenced shoreface or lower foreshore. High accumulation rates across the seagrass banks resulted in their rapid buildup to the base of the tidal zone, where they were locally transgressed by thin, intertidal sand sheets (Facies 5-A), composed largely of well-sorted, reworked quartz, which may have been periodically subaerially exposed. Populations of small, robust A-form *Nummulites* (Facies 3) thrived on sparsely or seasonally vegetated substrates in the (relatively) nutrient-rich conditions close to these banks. The presence of these A-form *Nummulites* communities associated with vegetated environments is perhaps significant, because *Nummulites* have never previously been identified as seagrass dwellers. It suggests that like many modern larger soritid foraminifera, which live on a wide range of substrates including seagrass, some (?small) species of *Nummulites* may have lived on marine vegetation.

The sediments that constitute Facies Association B occur in the middle part of the studied section (17 m to 330 m on log 3; see Fig. 11), and have a combined thickness of over 300 m, the greater part of which is represented by Facies 4 (which constitutes the bulk of the sediment logged during this study, with a total thickness of approximately 250 m). This association represents deposition in a slightly deeper, lower-energy, more basinward environment than that inferred for Facies Association A. Much of the sediment (Facies 4) accumulated in a protected, shallow (< 30 m deep), low-energy lagoonal environment, sparsely or patchily vegetated by seagrasses, articulated CRA, and calcareous green algae, and (possibly) patchily colonized by patch reefs. The activities of numerous infaunal organisms resulted in extensive bio-retexturing of this sediment. It is suggested that the presence of dense seagrass meadows (Facies 2) in this environment may represent the progradation of the shallow subtidal seagrasses into the lagoon, following rapid buildup of the banks to low-tide level due to high sediment accumulation rates. *Nummulites* communities, dominated by large, robust A-forms (Subfacies 6-A) thrived in distal parts of the lagoon. Periodic high-energy (?storm) events are possibly suggested by the presence of concentrically laminated rhodoliths and probable tubular tempestites and scours in Facies 4, the local presence of allochthonous *Nummulites*, *Assilina*, and *Discocyclina* debris, and also by cross-bedded sandy peloidal limestones (overlying *Alveolina* lags on scoured surfaces) of Subfacies 5-B. The teredinid accumulations in Facies 4 (and other evidence from Rusayl Fm.) indicate that mangroves were growing along the contemporary shoreline throughout deposition of the Seeb Fm.

Facies Association C occurs in the uppermost part of the studied section (330 m to 397 m on log 3; see Fig. 11) and can broadly be divided into two environments, separated by low-relief shoals of largely parautochthonous LBF tests (dominantly *Nummulites* and *Assilina*) that probably formed close to FWWB (Subfacies 6-B). Behind these shoals developed protected, thoroughly bioturbated lagoons with (possible) patch reefs, where a diverse assemblage of foraminifera, dominated by *Alveolina*, thrived on muddy sands patchily vegetated by seagrasses and calcareous red and green algae (Facies 4). Communities of robust, *in situ* A-form *Nummulites* lived in (probably) sparsely vegetated environments in the immediate lee of these shoals (Subfacies 6-A). In shallow fore-shoal environments, *Nummulites* coexisted with saddle-shaped *Discocyclina* on muddy substrates, which were locally colonized by dasycladacean green algae and also (possibly) seagrasses (Subfacies 6-C). Interbedded with these fore-shoal deposits are sediments indicative of shallower, more protected environments (Subfacies 6-D), which may have been created by the emplacement of more distal shoals of Facies 6-B. Occasional storms reworked the shoals and spread thin sheets of fine-grained, well-sorted quartz (Subfacies 5-B) across back-shoal environments. Previous studies indicate that the Seeb Fm. was deposited on a storm-influenced ramp, on a windward tropical coast facing a large expanse of open ocean towards the east. However, despite this apparently high-energy setting, it is interesting to note the general lack of evidence for storm influence in the Seeb Fm. at Al Khod, which is limited to SCS near the base (Facies 1), and also the thin, erosionally based sandy peloidal limestones of Subfacies 5-B. Such features have also been noted in studies of the Seeb Fm. from other locations (e.g., Nolan et al. 1990; Racey 1995), although the observation in the former study of an increasing occurrence of grainstone textures towards the west, at Khasaf, appears to indicate that higher energy conditions existed elsewhere on the platform. However, comparison of the Seeb Fm. with modern, analogous windward platforms (such as the Rio Grande do Norte continental shelf, northeast Brazil; Testa and Bosence 1998, 1999), which may be characterized by large transverse (subaqueous) dunes and sand ribbons up to 12 km long, reinforces the idea that the Seeb Fm. is not typical of such regimes. The absence of similar large-scale bedforms in the Seeb Fm. may indicate the presence of more distal barrier facies during deposition of the unit. Evidence for such a barrier may have been eroded during uplift related to isostatic rebound following earlier thrust loading (Jones and Racey 1994), although horst blocks identified by Mann et al. (1990) offshore (and running parallel to) the Batinah Coast may have formed an offshore barrier during the Eocene, and it seems likely that such structures would have influenced energy levels during deposition of the Seeb Fm. Alternatively, low energy levels may indicate deposition in a protected embayment (at least at Al Khod). Although the *Nummulites–Assilina* packstones of Subfacies 6-B have already been interpreted as a barrier facies, it seems unlikely that their low relief and high micrite content reflect deposition as barriers taking the full force of an open, windward coast. Deposition behind a more distal barrier, or within a protected embayment at Al Khod, is perhaps further suggested by the paucity of planktonic foraminifera in the Seeb Fm. (noted during this study, and also by White 1994 and Racey 2001), which may indicate only limited connection to the open ocean (cf. Murray 1976). Further evidence of protection during deposition may also be indicated by the presence of



	Facies Associations		
	A	**B**	**C**
Facies	Rusayl Fm. 1 2 3 5-A	2 4 6-A 5-B	4 6-A 6-B 6-C 6-D 5-B

FIG. 11.—Logs of the Seeb Fm. at Al Khod (see Fig. 3 for log locations), showing the distribution of the three facies associations. Facies key as for Figure 5.

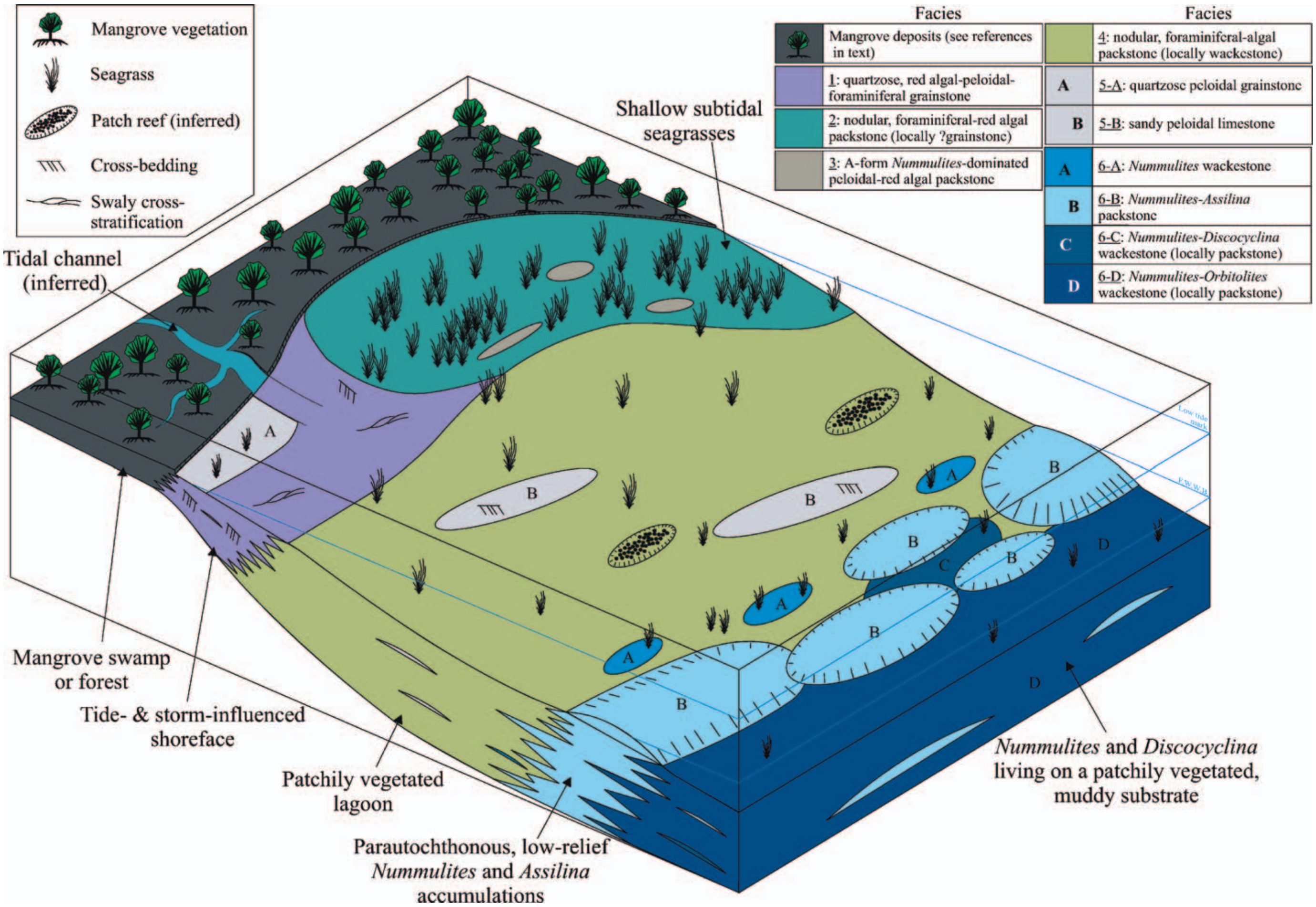


FIG. 12.— Depositional model for the Seeb Formation at Al Khod. The Seeb Fm. in the study area was deposited on a windward, tropical coast, in a protected, (probably) structurally controlled, mangrove-fringed embayment. In this embayment, a shallow, thoroughly bio-retextured lagoon (possibly with scattered patch reefs) developed behind parautochthonous biostromal reef mounds composed of nummulitid larger foraminifera. Seaward of these barriers, *Nummulites* and *Discocyclina* lived on or below fair–weather wave base (although probably shallower than 30 m) muddy, sparsely vegetated substrates. The lagoon locally contained dense, shallow-subtidal seagrass stands and supported a diverse assemblage of foraminifera, dominated by elongate *Alveolina*. Communities of large, robust A-form *Nummulites* thrived in the most distal parts of the lagoon.

mangroves (which are today generally restricted to protected environments; e.g., Gischler and Lomando 2000). In addition, fan-shaped paleocurrents obtained from Facies 1 (Beavington-Penney 2002) may indicate divergence of the current after passing through a flow constriction (such as a tidal channel through barrier islands?) (cf. Anastas et al. 1997), or perhaps refraction of currents in a semi-enclosed, embayed area. Interestingly, such an embayment could have been produced by NNE–SSW oriented transtensional faults (and associated normal and strike-slip faults) in the Al Khod area (Fig. 3), which were active during deposition of both the Seeb Fm. and the underlying early Eocene Rusayl Fm. (S. Hanna, personal communication 2004), and most likely account for the significant thickening of the former and thinning of the latter, which can be clearly seen in Figure 3.

Earlier studies of the Seeb Fm. have noted that facies belts on the ramp show little lateral variation along the Batinah Coast, and there is no evidence for a continuous reefal rim (e.g., Racey 1995, 2001). However, the presence at Al Khod of a package of shallow-subtidal sediments several hundred meters thick (Facies 4) is hard to explain in the context of such an environment, because thick aggradational shallow water packages are rare on ramps, since their low angle results in rapid lateral shifts of facies in response to sea-level change. Rather, such an accumulation appears to be more indicative of a rimmed, flat-topped platform, where thick aggradational packages can develop behind a reefal or shoal-belt rim (Tucker and Wright 1990, Chapter 2). It is hard to resolve this issue because there is no outcrop evidence for a significant break in slope or the presence of platform-margin shoal belts.

The studied section of the Seeb Fm. appears to form a single transgressive unit, deepening upwards from the fluvial and lagoonal sediments of the Rusayl Fm., through SCS- and cross-bedded shoreface sediments at the base of the Seeb, and the deeper, lagoonal sediments that form the bulk of the sediment, to the more distal nummulitid shoals and *Discocyclina*-rich foreshoal deposits. But more detailed evidence for relative sea-level change in much of the Seeb Fm. is curiously absent. For example, the thick package of nodular, indistinctly bedded lagoonal sediments, which consists largely of one facies type, shows no evidence of hiatus surfaces (such as hardgrounds and subaerial exposure) or cyclicity (i.e., shallowing-upwards cyclothems). This contrasts with the base of the section, where the Rusayl Fm. shows marked vertical and lateral facies changes, reflecting sea-level variation (Keen and Racey 1991), and sea-level fluctuations are also indicated by the interbedding of Seeb Fm. shoreface grainstones with the fluvial and lagoonal mudstones of the Rusayl Fm. (see Fig. 8A) (although this may represent progradation of the latter). This lack of evidence for sea-level change in much of the Seeb Fm. is surprising, inasmuch as the Seeb Fm. at Al Khod was deposited over a period of approximately 7.8 Ma (Jones and Racey 1994), spanning four complete and two partial third-order global sequences of Haq et al. (1987). Sediments deposited in similar settings throughout the Mesozoic and Paleozoic typically display shallowing-upwards cyclothems, and the lack of evidence for third-order (and higher-order) sea-level change throughout much of the shallow subtidal Seeb Fm. suggests an unlikely balance between subsidence, long-term (eustatic) sea-level change, and sedimentation rate. In addition, the calculated accumulation rate of the Seeb Fm. (discussed below) is significantly lower than that measured in similar modern environments. Below we examine the possible mechanisms responsible for the accumulation of this thick package of homogeneous, acyclic sediments and ask how such sediments relate to recent studies of sediment production and facies preservation across modern carbonate platforms.

DISCUSSION: CONTROLS ON THE DEVELOPMENT OF ACYCLIC, HOMOGENEOUS, SUBTIDAL SEDIMENT IN THE SEEB FORMATION

Facies 4 presents several problems: (1) it was probably deposited in a high-productivity (i.e., high rate of sediment production) seagrass-vegetated setting, yet calculated net accumulation rate was low, and there are no hiatal or erosion surfaces to explain the missing sediment and time; (2) the unit was deposited in very shallow water over a long period of time, yet it exhibits no apparent depth-related changes or cyclicity; and (3) it exhibits a remarkable lack of facies diversity, despite being deposited in a setting that today is characterized by diverse ecological and depositional zonation.

The bulk of the Seeb Fm. sediment was deposited in a lagoonal setting (i.e., Facies Association B). Published rates of sediment production and accumulation from Holocene tropical lagoons are typically in the range of 0.6 mm yr^{-1} (Gischler 2003, and references therein) to 1 mm yr^{-1} (Strasser and Samankassou 2003, and references therein), although very high rates of sediment production, and accumulation rates of 2 mm yr^{-1}, have been noted within some sub-environments (particularly seagrass meadows) of lagoons (e.g., Brasier 1975b; Belperio et al. 1988). Seagrasses supply large quantities of biogenic $CaCO_3$ to the substrate in the form of epiphytes and sheltered organisms, i.e., those living in or on the sediment below the seagrass cover (e.g., Nelsen and Ginsburg 1986; Bosence 1989). High sediment accumulation rates (relative to adjacent settings) in seagrass beds have been shown to reflect the baffling effect of seagrass blades, which promotes the settling out of fine particulate sediment (Scoffin 1970), and the binding and stabilization of the sediment by dense rhizome networks associated with most seagrass species, which aids sediment accumulation (Bosence 1995). Taking a uniformitarian approach, and assuming that an accumulation rate of 1 mm yr^{-1} represents a reasonable average for tropical lagoons, the Holocene data above suggest that during deposition of the Seeb Fm. a package of sediment at least 7.8 km thick could potentially have built up. However, the thickness of the Seeb Fm. at Al Khod is approximately 590 m—more than an order of magnitude less. We cannot be certain how much sediment was removed by the regional unconformity which overlies the Seeb Fm., although the general lack of mechanical and chemical compaction features in Seeb Fm. bioclasts, and the organically immature character of shales of the underlying Rusayl Fm. (Goodall et al. 2005), suggest that it cannot have been significant. Making allowance for shallow-burial compaction of possibly up to 15% (based on data in Bond and Kominz 1984; Goldhammer 1997), the accumulation rate of the Seeb Fm. appears anomalously low. However, such discrepancies are a common feature in the rock record, where long-term production rates of ancient sedimentary successions are typically one or more orders of magnitude less than those measured in modern, shallow marine, tropical environments (e.g., Sadler 1981; Tipper 1983; Sadler and Strauss 1990; Wilkinson et al. 1991; Schlager 2000).

The lack of abundant erosion surfaces in Facies 4 suggests that it is unlikely that storm-induced erosion (export) accounts for a significant proportion of the missing sediment. It can perhaps be speculated that sediment has been lost from the Seeb Fm. during early diagenesis; recent studies have suggested that early dissolution in shallow marine, tropical and subtropical waters, triggered by undersaturation caused by microbial decay processes, can lead to massive aragonite loss (e.g., Cherns and Wright 2000; Wright et al. 2003). Although formerly aragonitic mollusks and dasycladacean green algae are locally preserved (as ferroan, and occasionally nonferroan, calcite spar) in the studied outcrops, this does not preclude the possibility of significant aragonite loss through dissolution, because some bioclasts may have been more vulnerable to dissolution than others, and gradients in shell preservation—related to patchily intensified dissolution in bioturbated sediments—have been documented in other limestones (Sanders 2003, and references therein). The nodularity of many of the facies identified in this study may be a consequence of early precipitation of low-magnesium calcite cement (e.g., Munnecke et al. 1997), with cement distribution influenced by bioturbation, resulting in lateral variations in early lithification and aragonite loss.

Even if we assume that up to 50% of the volume of the original sediment has been lost due to early dissolution (cf. Sanders 2003, and references therein), there still remains a significant discrepancy between the measured thickness of the Seeb Fm. and the potential thickness based upon the modern accumulation rate quoted earlier. The uniformity of lagoonal sediment without periodic subaerial exposure would require an unlikely balance between sediment production rate and the creation of accommodation space related to subsidence, damping the effects of both sediment aggradation and eustatic sea-level oscillations. The Seeb Fm. was deposited on a passive continental margin (Mann et al. 1990), where subsidence rates might be expected to have been in the range 0.01–0.04 mm yr^{-1} (based on data in Allen and Allen 1990, p. 59, fig. 3.12b). Such rates are far less than the sediment production rates in Holocene lagoons, and it seems likely, given this scenario (and the low-amplitude nature of sea-level fluctuations in the Eocene greenhouse world) that sediment would have rapidly filled up the available accommodation space. In view of this, the lack of exposure surfaces in the Seeb Fm. is hard to explain, and appears to contradict the observation of Nolan et al. (1990) that the sedimentary evidence of transgression and regression during the Paleogene in the Oman Mountain belt generally follows the cycles of Haq et al. (1987).

One possibility for the lack of hiatus surfaces and cyclicity in Facies 4 is that any evidence of these may have been destroyed during biological reworking of the sediment. Numerous studies have demonstrated that bioturbation by modern infaunal sediment dwellers and burrowers such as crustaceans and echinoids can have a profound effect on the primary depositional features of shallow marine sediments, destroying stratification and detailed lithological variations (e.g., Shinn 1968; Enos 1977; Tudhope and Scoffin 1984; Wanless and Tagett 1989; Tedesco and Wanless 1990, 1991, 1995; Pedley 1992). This process can occur over very short time scales: Thayer (1983) calculated that individual large infaunal burrowers can disturb up to $4 \times 10^2\ \mathrm{cm}^3$ of sediment per day, and Wanless et al. (1988) estimated that the entire upper 1 m of the sediment on the Caicos Platform is totally recycled every 100–300 years. Although Facies 4 generally lacks distinct burrows, dense meshworks of horizontal burrows exposed in hypichnial relief on basal bedding planes (Fig. 9C) appear to indicate that intense biological reworking has thoroughly modified this facies. In addition, seagrasses (which were present in the lagoon) can also modify shallow marine sediments; the rhizomes and roots of seagrasses physically modify the sediment up to 2 m below the sediment–water interface (Enos 1977; Wanless et al. 1995). The burrowing

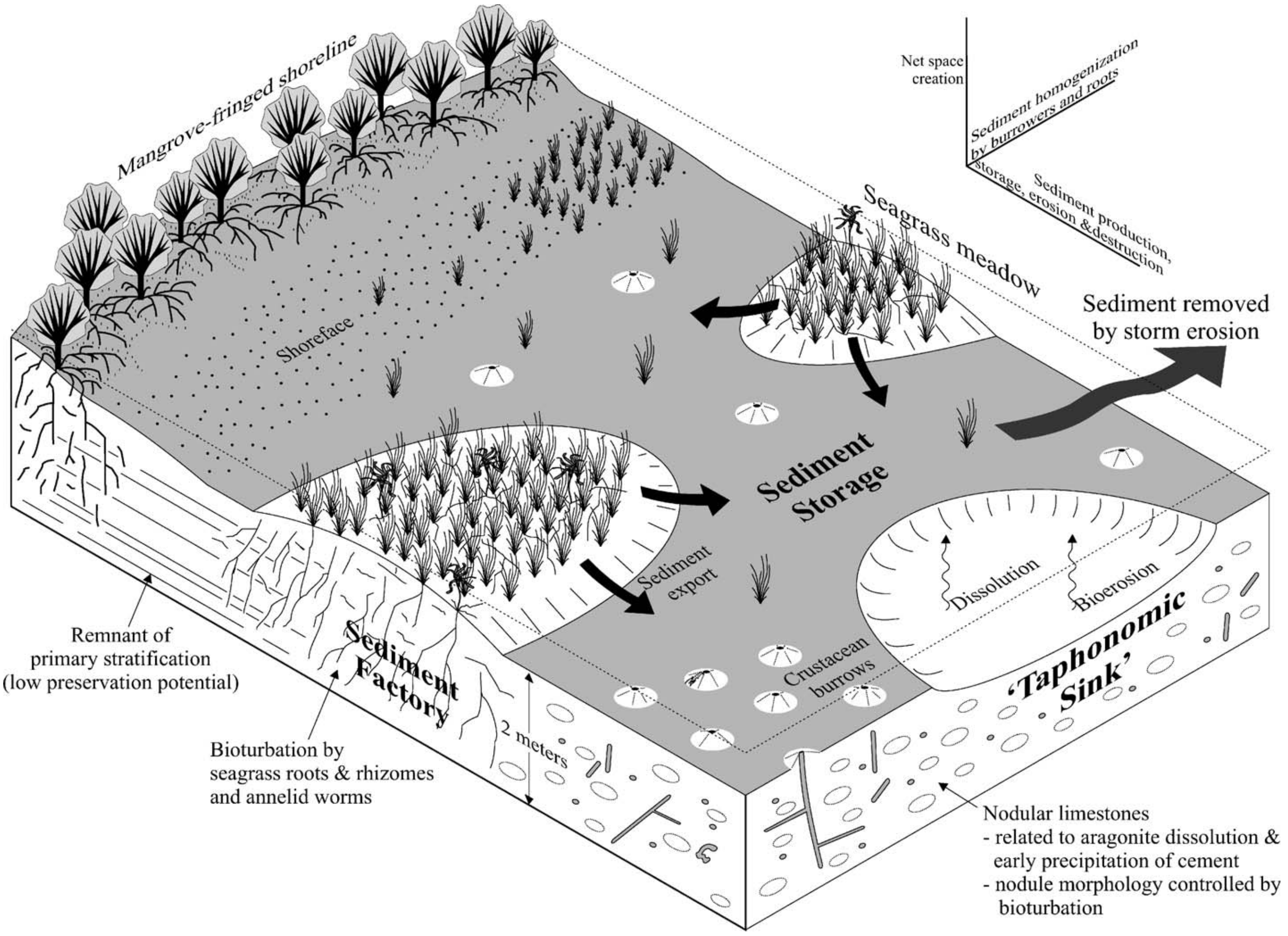


FIG. 13.—Model of the development of acyclic, homogeneous, lagoonal sediments during deposition of the middle Eocene Seeb Fm. Primary stratification is destroyed by burrowing organisms and the roots of seagrasses and mangroves. Bioturbation and early precipitation of cement result in sediment becoming increasingly nodular. Small-scale spatial and temporal variations in areas of sediment production, storage, and destruction are mobile over short time scales, and so local facies variations become homogenized and time-averaged. Although different facies occur in the whole succession, it is unclear how many represent true depositional facies or time-averaged composite facies.

of annelid worms associated with seagrasses has also been shown to destroy bedding (Pusey 1975). It seems likely that the roots of mangroves (which were most likely fringing the shoreline during deposition of Facies 4) would also have destroyed primary fabrics and bedding. Indeed, it has been suggested that the lack of peritidal cyclothems (which characterize carbonate platform interiors of Precambrian to Late Cretaceous age) in the Cenozoic may coincide with the spread of mangroves (Wright and Azeredo 2004). It seems most probable that the combined disturbance caused by infaunal sediment burrowers and dwellers, and by marine grass and intertidal mangroves, would have been more than sufficient to rework the sediment completely, destroying primary depositional surfaces and detailed lithological variations (including evidence of cyclical facies change), i.e., preserved facies represent "taphofacies" rather than "depofacies." Of course, this scenario raises questions about why other facies are preserved in the studied succession. Wouldn't homogenization have destroyed any subtle facies differences in the lagoons? Maybe the preservation of other facies types may reflect significant sea-level change, or a subtle balance between sediment production, taphonomic loss, and accommodation space creation or loss, allowing, for example, the seagrass beds of Facies 2 to prograde into the lagoon.

It perhaps needs to be considered that published sediment accumulation rates (modern and/or ancient) are incorrect. High rates of sediment accumulation recorded in modern settings may be unrepresentative of the rock record, because they are a response to high short-term rates of accommodation creation related to the glacioeustatic rise during the Holocene (which has produced rates of reef growth of 5–12 mm yr^{-1}; Bosscher and Schlager 1992). An alternative view has been advanced by Pittet et al. (2000), who suggested that production rates on both modern and ancient platforms were actually similar, and the lower accumulation rates commonly inferred for the ancient successions may represent increased basinward transport of carbonate mud. However, it can also be speculated that if rates were the same, it is the modern accumulation rates that are too high, rather than the ancient rates being too low, because the published (typically high) modern sediment production data are being incorrectly converted into accumulation rates. Recent studies (e.g., Wilkinson et al. 1999; Demicco and Hardie 2002; Schlager 2003; Wilkinson and Drummond 2004; Yang et al. 2004) have shown that sediment production in modern, shallow marine settings is not uniform over the platform. At any one time, sediment is being produced in local "factories" (from where it may be exported onto other parts of platform), whilst other areas are sites of sediment destruction (sediment sinks) (e.g., Perry 1998, 2000; Wright and Cherns 2004); intermediate areas are sites of sediment storage (Fig. 13). This mosaic of sediment production, storage, and destruction is mobile over short time scales (hundreds to thousands of years), and below the sedimentologically and taphonomically active zone sediments are time averaged, and the distinction between factories and sinks is largely destroyed (Wright and Burgess 2005)—a process which may explain the apparently anomalous coexistence in the Seeb Fm. of infaunal echinoids (which are today restricted to largely unvegetated settings) and seagrass epiphytes, e.g., in Facies 4 and 6-A. Therefore, modern accumulation rates as high as 1–2 mm yr^{-1} (which are typically measured in very productive parts of the platform such as seagrass beds) do not reflect an overall, platform-wide rate, because only a small percentage of the platform is producing at any one time. Before modern accumulation rates can be applied to the rock record, locally high production rates need to be balanced against areas of nondeposition and erosion on the same platform to derive a long-term average accumulation rate. If the sediment production rate during deposition of the Seeb Fm. was low, the balance between subsidence and sediment production would have been more evenly balanced than was speculated earlier, which may help explain why sediment did not rapidly fill available accommodation space in a slowly subsiding, passive-margin setting. It could be envisaged that under certain conditions sediment would accumulate without being subaerially exposed, or without the carbonate factory ever drowning, even in greenhouse periods characterized by low-amplitude sea-level fluctuations. Loss of sediment through early dissolution of aragonite may also have helped bridge the gap between sediment production rate and subsidence during deposition of the Seeb Fm.

To summarize, it seems likely that the anomalously low calculated accumulation rate of the Seeb Fm. is a consequence of comparison with unrepresentative, localized high rates of modern sediment production. Such rates are often based on highly productive factories such as seagrass beds, and extrapolated uniformly across platforms, whilst recent studies have shown that modern platforms show highly variable rates of sediment production, and average rates across platforms are likely to be much lower than the 1 to 2 mm yr^{-1} often cited. Remaining discrepancies between modern and Seeb Fm. sediment accumulation may in part represent significant early loss of aragonitic components from the Seeb Fm. Given this scenario, "missing time" in the Seeb Fm. (and other ancient successions) is most likely not simply a consequence of intervals of nondeposition or erosion but reflects low long-term accumulation rates, as a result of sediment production by a complex suite of processes, some of which actually resulted in loss of carbonate through bioerosion, abrasion, and dissolution. Evidence for cyclicity and sea-level change in the Seeb Fm. (and potentially any shallow marine succession deposited in the Cenozoic, after the evolution of seagrasses and mangroves) has been removed by thorough bio-retexturing of the sediment by burrowing organisms and the roots of marine vegetation. If the conclusions of our study are universally applicable throughout the Cenozoic, it means that shallow marine carbonate areas influenced by seagrasses, mangroves, and other marine vegetation are poor sites for the preservation of fine-scale sedimentary cycles. This has obvious implications for stratigraphic correlation in such sequences, the development of cyclostratigraphic models, and also reservoir models, because primary porosity in platform-interior successions in the older rock record is often concentrated in grain-rich cycle tops (Moore 2001, and references therein).

CONCLUSIONS

The middle Eocene Seeb Fm. is an example of one of the earliest modern carbonate systems, because it was associated with mangroves and seagrasses. Apparent acyclicity within the thick package of lagoonal sediments that constitute much of the Seeb Fm. at Al Khod, and the general lack of evidence for sea-level change in the studied sediments, are likely to be a consequence of the destruction of "missing time" horizons and primary fabrics by burrowing organisms and the roots of marine vegetation. It seems possible that a lack of peritidal cyclothems, which have typified sediments deposited in shallow marine carbonate settings throughout much of the rock record, may be common to many Cenozoic deposits, a consequence of the spread of seagrasses and mangroves since the Late Cretaceous. This has clear implications for stratigraphic correlation in such shallow marine limestones, and the development of cyclostratigraphic and reservoir models.

We would also like to suggest that the importance of "missing time" horizons in ancient sediments may have been overstated by some authors, and that discrepancies in the literature between modern sediment accumulation rates in shallow, tropical settings and much lower long-term production rates in ancient successions are largely a consequence of the extrapolation of localized modern high production rates to large (platform)–scale areas. Modern sediment production and accumulation rates may be much lower than previously thought because they are typically measured in highly productive areas such as seagrass beds and do not take into account the highly variable nature of carbonate production, storage, erosion, and destruction across platforms. Therefore, sediment production and accumulation rates taken over the whole platform are likely to be much lower than many published rates, and so far less "missing time" needs to be inferred for ancient sediments to account for any imbalance between modern and ancient sediment accumulation rates.

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Authors Queries

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