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# Microbial-foraminiferal episodes in the Early Aptian of the southern Tethyan margin: ecological significance and possible relation to oceanic anoxic event 1a

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## ABSTRACT

Two regionally significant microbial-foraminiferal episodes (~150 kyr each) occur within the Early Aptian shallow marine platform in Oman and throughout eastern Arabia. The stratigraphically lower of these two intervals is characterized by isolated or coalescent domes that share similarities with modern, open-marine stromatolites from the Exuma Cays, Bahamas. The upper interval is predominantly built by a problematic *Lithocodium/Bacinella* consortium in buildup and massive boundstone facies. Based on high-resolution chemostratigraphy, these shoalwater intervals are coeval with oceanic anoxic event 1a (OAE1a; Livello Selli). Field evidence demonstrates that the buildup episodes alternate with stratigraphic intervals dominated by rudist bivalves. This biotic pattern is also recognized in other coeval Tethyan sections and is perhaps a characteristic shoalwater expression of the OAE1a. The short-lived regional expansions of this microbial-foraminiferal out-of-balance facies cannot be explained by local environmental factors (salinity and oxygen level) alone and the buildup consortia do not occupy stressed refugia in the absence of grazing metazoans. Judging from recent analogues, the main fossil groups, i.e. microbial assemblages, macroalgae, larger sessile foraminifera, and rudist bivalves, all favoured elevated trophic levels but with different tolerance limits. The implication of this is that the influence of palaeofertility events, possibly related to OAE1a, on carbonate platform community structures must be investigated. The observations made in these coastal sections are a significant first step for the improved understanding of the Early Aptian period of biotic, oceanic and climatic change.

**Keywords** Carbonate buildups, Cretaceous, OAE1a, Oman, palaeofertility, runoff, Tethys.

## INTRODUCTION

'Cretaceous anoxic events: from continents to oceans' is the title of a classic publication by Jenkyns (1980). Subsequent research dealing with oceanic anoxic events (OAEs), however, has been biased towards black shale deposition in hemipelagic and pelagic sections and Ocean Drilling Program (ODP) core material (e.g. Weissert *et al.*, 1985, 1998; Wetzel, 1985; Arthur *et al.*, 1990; Weissert & Bréhéret, 1991; Jenkyns *et al.*, 1994; Erbacher *et al.*, 1996; Menegatti *et al.*, 1998; Hochuli *et al.*, 1999). In contrast, only a few studies have focused on the OAE1a time-equivalent facies of the shallow epicontinental seas, forming the link between the continents and the oceans (Ferreri *et al.*, 1997; Pittet *et al.*, 2002; Hillgärtner *et al.*, 2003). With reference to the Early Aptian OAE1a, this bias is partly related to the drowning of many Tethyan platforms (e.g. Schlager, 1981; Jenkyns & Wilson, 1999), expressed as a lack of adequate sections, and partly due to the scarcity of precise stratigraphic correlations of basinal and shallow marine facies (Ferreri *et al.*, 1997).

The present study documents and discusses two Lower Aptian stratigraphic intervals in the shallow marine carbonate platform of Oman. The facies of these intervals are characterized by short-lived (~150 kyr) expansion pulses of an out-of-balance facies including what are interpreted to be microbial communities consisting of macro-algae, and larger sessile foraminifera in buildups and massive bindstone facies (Fig. 1A). Judging from chemostratigraphic and biostratigraphic evidence presented here, these algal-foraminiferal-microbial episodes represent the shoalwater equivalents of the oceanic OAE1a black shales.

Whereas long-term fluctuations in the abundance of microbial carbonates have been attributed to fluctuations of Phanerozoic seawater geochemistry and eukaryote competition (Riding, 2000), short-lived imbalance community episodes are rarely described (Schlager, 2003) and poorly understood features. In order to document the Oman examples, the facies and biota, the buildup morphologies, the buildup evolution and the density per unit area are described. Based on field observations and comparative studies between the fossil biota in these sections and modern life forms, several working hypotheses for the possible causal relationship between the OAE1a event and algal-foraminiferal-microbial episodes are discussed.

## GEOTECTONIC SETTING OF THE STUDY AREA

During the Middle Cretaceous, the Arabian Peninsula was located approximately at 8°S (Hughes, 2000). Owing to the globally high sea level (Hardenbol *et al.*, 1998), broad portions of the Arabian craton were flooded and carbonates were deposited on an extensive platform (e.g. Murris, 1980; Hughes Clarke, 1988; Le Métour *et al.*, 1995; Sharland *et al.*, 2001). The interval studied, the Late Barremian through Early Aptian Qishn Formation, forms part of these autochthonous shelf deposits and largely corresponds to the Upper Kharaib and the Lower Shu'aiba formations of northern Oman (Figs 1 and 2; van Buchem *et al.*, 2002; Pittet *et al.*, 2002; Hillgärtner *et al.*, 2003; Immenhauser *et al.*, 2004).

The carbonate rocks of the Qishn Formation onlap the approximately north–south trending Haushi-Huqf High (Fig. 1B). In this region, bedding is subhorizontal, dipping westward at 2–3° towards the Oman Interior basins (Fig. 1B; Immenhauser *et al.*, 2004).

Two field areas of in total ~ 100 × 20 km were investigated: a northern outcrop belt near Wadi Jarrah and a southern outcrop belt near Wadi Baw (Fig. 1C). In both areas, the Qishn Formation is exposed in elongated table mountains and in low-relief hills protruding from sabkha plains that provide full exposure of bedding surfaces within the Qishn Formation representing 1000s of $m^2$ of the palaeo-seafloor.

## METHODS APPLIED AND PRESERVATION OF CARBONATE MATERIALS

Two hundred and sixty-nine chalky micrites were analysed for stable isotopes on a ThermoFinnigan MAT 252 gas source ratio mass spectrometer. Repeated analyses of carbonate standards and replicates indicate a reproducibility of better than $\pm 0{\cdot}1‰$ for $\delta^{18}O$ and $0{\cdot}05‰$ for $\delta^{13}C$. All isotope results are reported in ‰ relative to the VPDB standard. Strontium isotope analysis was performed on 24 low-Mg calcite rudist specimens, selected for their pristine trace element composition (Sr, Mg, Mn, Fe). Refer to Steuber (2001) for details of the analytical procedure.

Prior to geochemical analysis, 62 thin sections were investigated for evidence of burial diagenetic alteration by transmitted light and cathodoluminescence using a cold-stage cathode luminescence microscope operating at 10–14 kV accelerating voltage, 200–300 μA beam current, and a beam diameter of 4 mm. Based on this approach and judging from trace-elemental data (Immenhauser *et al.*, 2004), the degree of post-depositional diagenetic alteration of the chalky limestones in these sections is considered to be minor. This is related to the very shallow burial depth of these sections (200 m ± 50 m) and the arid post-exhumation climate in Oman. Exceptions are intervals affected by either Cretaceous or early Holocene meteoric diagenesis. For geochemical analysis, these altered intervals were avoided. Refer to Immenhauser *et al.* (2004) for details of the diagenetic history of the Qishn Formation carbonate rocks.

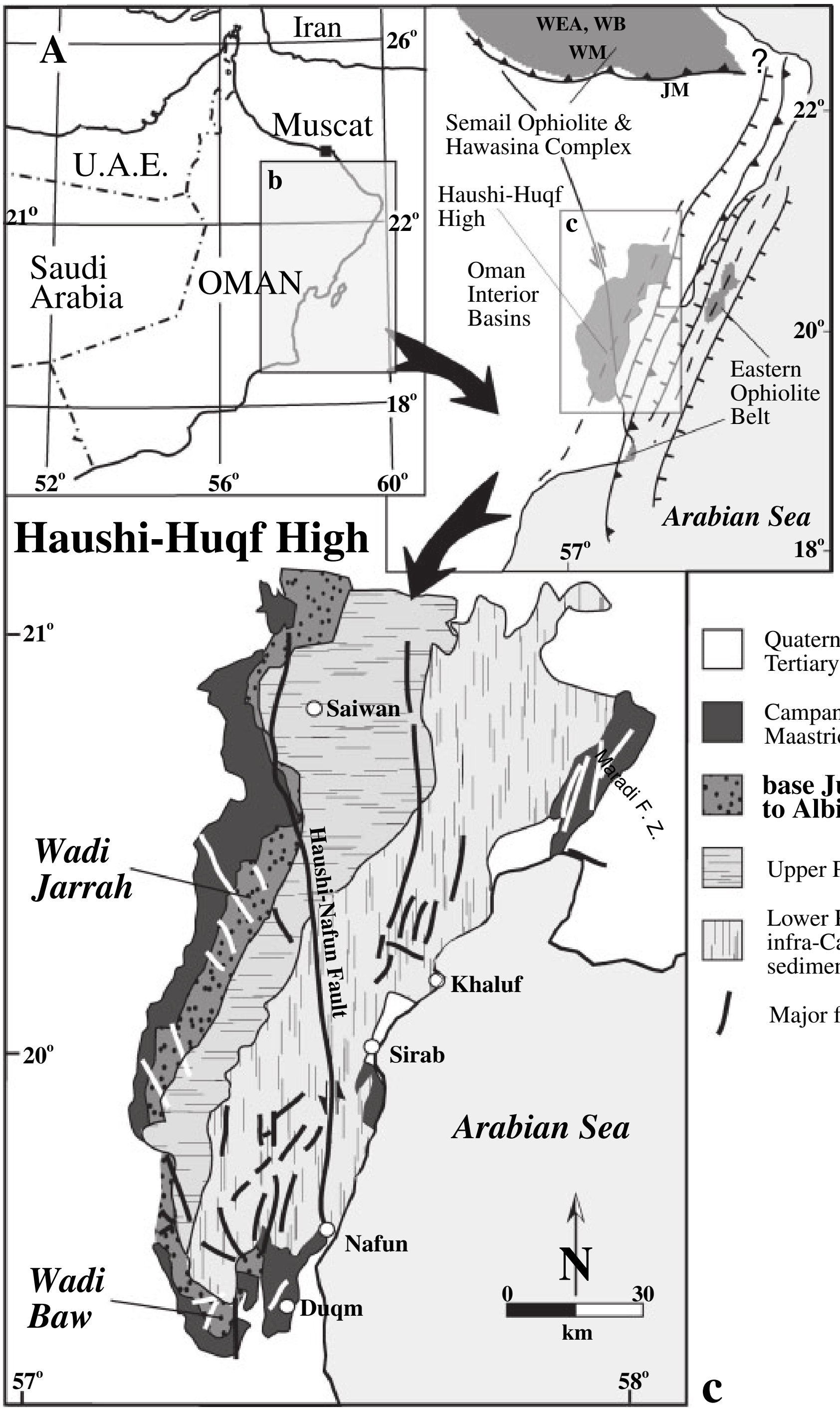


**Fig. 1.** (A) Regional map of eastern Arabia and (B) eastern Oman showing the position of the Haushi-Huqf area. Approximate positions of the following localities are indicated: Jabal Madar (JM); Wadi el Assyi (WEA); Wadi Baraka (WB); Wadi Mu'aydim (WM). (C) Geological map of the Haushi-Huqf area indicating the location of the northern (Wadi Jarrah) and southern (Wadi Baw) study areas.

## DEPOSITIONAL ENVIRONMENTS

The Early Aptian depositional environment of the Qishn Formation in the Haushi-Huqf area was mainly that of a north–south elongated shallow, locally restricted platform with only minor topographic relief, perhaps separated from the Tethyan Ocean to the east by emergent basement highs of the Haushi-Huqf High (Immenhauser *et al.*, 2000, 2004). To the west, the Haushi-Huqf High

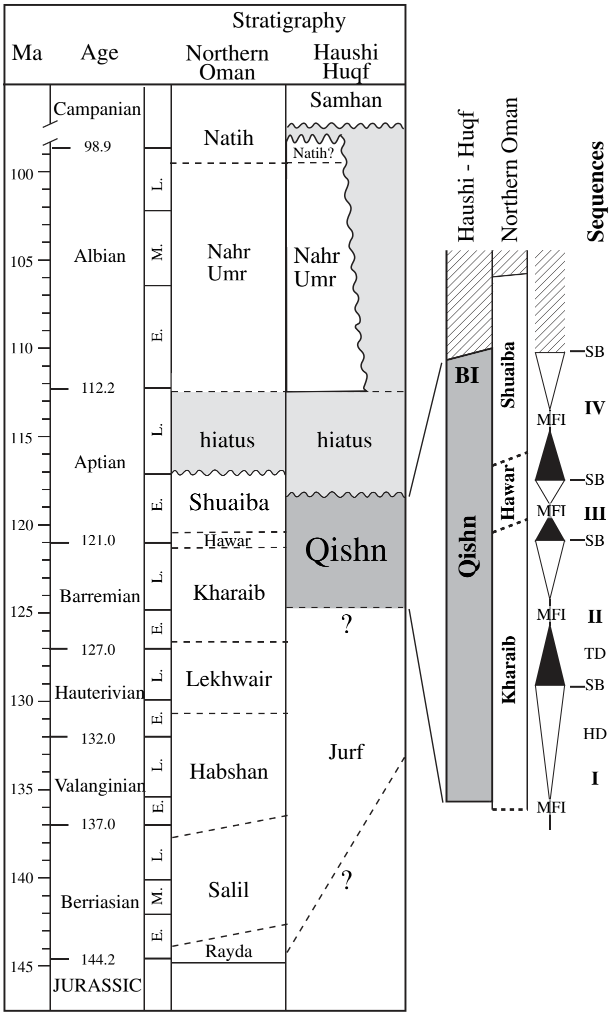


**Fig. 2.** Regional lithostratigraphy of Cretaceous units in Northern Oman in comparison to the stratigraphy in the Haushi-Huqf study area. To the right, large-scale sequences I through IV with corresponding transgressive deposits (TD) and highstand deposits (HD) are shown. Maximum flooding intervals (MFI) and sequence boundaries (SB) are marked. The stratigraphic position of the two buildup intervals (BI) is indicated.

deepened into the Oman Interior intrashelf basin, a shallow depression that opened northwestwards into the deeper Bab Basin (Fig. 3; van Buchem *et al.*, 2002).

As a consequence of the shallow average water depth over the proximal shoulder of the Haushi-Huqf High, stratigraphic units have tabular geometries and facies belts may be traced laterally over considerable north–south distances (100 km). In an east–west transect, i.e. perpendicular to the Aptian depositional belts, sedimentary environments change more rapidly (over 10s of km) both into the Oman Interior basins to the west and into the Tethyan Sea to the east (Immenhauser *et al.*, 2000).

### Sequence stratigraphic analysis

Sequence stratigraphic analysis showed that the Qishn Formation is composed of four large-scale depositional sequences reflecting regional relative sea-level changes with frequencies of the order of 1–2 Myr (Fig. 2; Immenhauser *et al.*, 2004). Sequences III and IV (Fig. 2) show a facies evolution from peritidal-dominated environments at the base to shallow subtidal-dominated environments at the top, suggesting an overall transgressive trend. The same transgressive trend can be observed in the correlative Hawar Member and the lower part of the Shuaiba Formation of northern Oman (Fig. 2; van Buchem *et al.*, 2002). Higher-frequency relative sea-level changes within the large-scale sequence architecture are indicated by regionally correlatable, metre-scale, cyclical changes in facies (Fig. 4).

The two buildup intervals of interest in this study form small-scale transgressive–regressive cycles within the highstand systems tract of the uppermost large-scale Sequence IV (Figs 2 and 5). The overall depositional environment of Sequence IV is an open to high-energy shallow platform with subtidal sand waves and rudist lithosomes (Fig. 4).

## BIOTA, ANATOMY AND FACIES OF BUILDUPS

Two buildup intervals are recognized within Sequence IV of the Qishn Formation. The carbonate buildups in these intervals are fundamentally different from each other in terms of their biota and morphology. The descriptive label 'buildup' is used here for these features and they are referred to as the 'lower' and 'upper' buildup intervals respectively (Fig. 4). 'Sediment buildups' in the stratigraphically lower interval show some of the characteristic features of coarse agglutinating thrombolites (Riding, 2000), and of modern stromatolites in open-marine environments from the Exuma Cays, Bahamas (e.g. Dravis, 1983; Reid *et al.*, 1995; Macintyre *et al.*, 2000). Similarities of the studied deposits with the Bahamian stromatolites include their morphology, their synsedimentary rigidity, essential to wave and current-resistant features, and perhaps their microbiological buildup consortia.

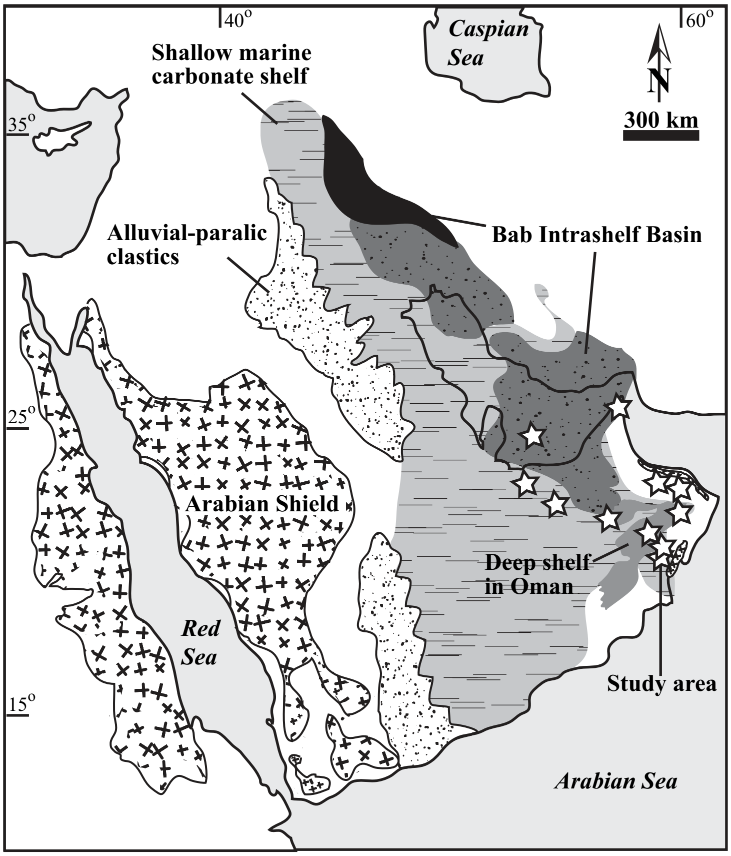


**Fig. 3.** Aptian palinspastic reconstruction of Arabia (after Hughes, 2000). The Bab intrashelf basin and a smaller depression in Oman are superimposed on the shallow marine carbonate shelf. Black and dark grey indicate basin and deep shelf and light grey points to shallow shelf. White indicates eroded or no data. Stars show position of some published Lower Aptian stratigraphic intervals dominated by *Lithocodium-Baccinella* facies (Hughes, 2000; van Buchem *et al.*, 2002; this study).

*Lithocodium aggregatum*, the dominant buildup component former in the upper interval, is considered to be the adult growth form of larger sessile foraminifera in the basal cavity of green algae (Schmid & Leinfelder, 1995, 1996). The *Lithocodium-Baccinella* buildups thus share similarities with algal-foraminiferal 'reefs' (Wood, 2001).

## Lower (sediment) buildup interval

### *Buildup dimensions, shape and facies*

The stratigraphically lower buildup interval is ~ 3 m thick and is easily recognized throughout the Qishn Formation outcrop belts in the Haushi-Huqf area due to its characteristic facies (Fig. 4). The buildups of the lower interval are isolated or coalescing dome-shaped heads with steep sides. Within each outcrop area, the buildups all seem to nucleate within the same stratigraphic level perhaps a few dm in thickness (Fig. 5A–C).

The carbonate buildups are elliptical with their longest sides typically having dimensions of 1·5–2 m but some reach 3·5 m in length (Figs 5A–C, 6 and 7). Where several buildups coalesce, clusters with dimensions of up to 5 m in length and about 2 m in width form. The ratio of longest to shortest buildup side is remarkably constant independent of the dimension of a given buildup (Fig. 6A). Buildup heights, where exposed in sections, typically reach 0·2–0·5 m (Fig. 5C).

The fabric of the lower buildups is sediment dominated and consists of medium-grained packstones, grainstones, and coarse rudstones or floatstones. Locally, the internal structure is stromatolitic to thrombolitic, but mostly it is structureless, open porous, and oncoidal to digitate. In thin sections, the microlamination is crudely expressed or blotchy and in places blurred by facies-selective, probably early Holocene, dolomitization of some of the buildups (Fig. 8A and B; Immenhauser *et al.*, 2004).

*Lithocodium-Bacinella* bound oncoids are locally present amongst the sediment intraclasts but are not the dominant component of these 'sediment' buildups (Fig. 8A and B). Rudist bivalves in life-position, mainly *Glossomyophorus costatus*, as well as a new rudist genus, new species, aff. *Glossomyophorus*, and sessile, chondrodonta-like oysters colonized some of these buildups but, on average, their volumetric significance is too low to act as framework builders (Fig. 8B; Immenhauser *et al.*, 2004).

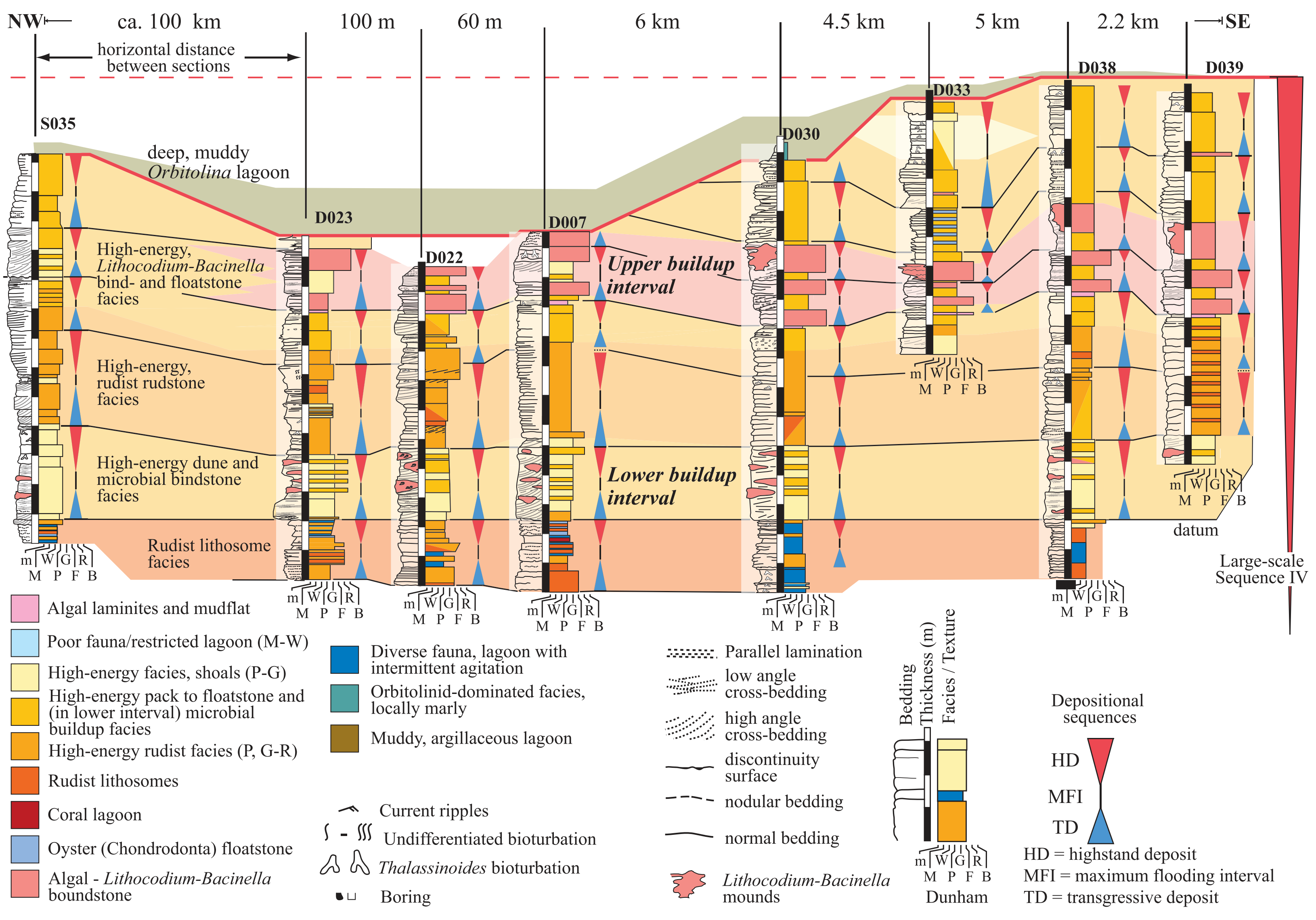


**Fig. 4.** North-west to south-east transect with lithostratigraphic sections measured through upper intervals of the Qishn Formation Sequence IV. The position of the two buildup intervals is indicated. Small-scale transgressive–regressive cycles are indicated to the right of each section. Tie lines between sections are sequence boundaries.

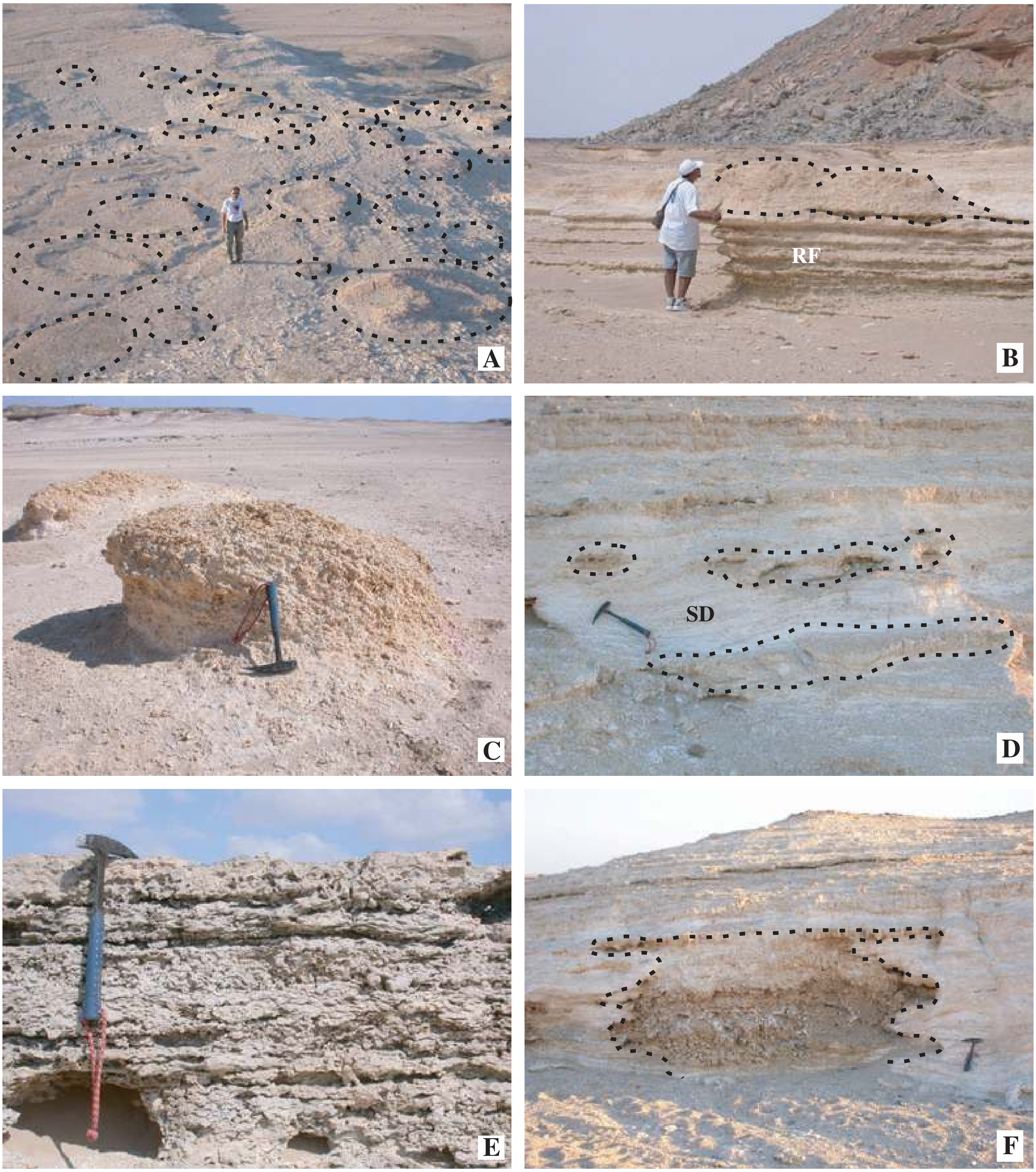


**Fig. 5.** (A) Lower buildup interval exposed near section D-007. Stippled lines indicate position of some buildups. (B) Lower buildup interval. Stippled lines indicate position of two buildups. Note sharp boundary with underlying rudist floatstone (RF). (C) Lower buildup interval near section D-033. Note brownish colour related to facies-selective late diagenetic dolomitization. (D) Upper buildup interval near section D-030. Proto-buildups (stippled line) formed by coalescing *Lithocodium-Baccinella* lumps (cf. Fig. 9). Note foresets of submarine dunes (SD). (E) Upper buildup level. Massive *Lithocodium-Baccinella* bindstone facies. (F) Upper buildup level near section D-033. The flat-topped buildup has reached base level and buildup accretion was predominantly lateral. Subsequently, the buildup has been covered by coarse rudstones. Note oncolithic aprons pointing to a buildup relief rising above the carbonate seafloor.

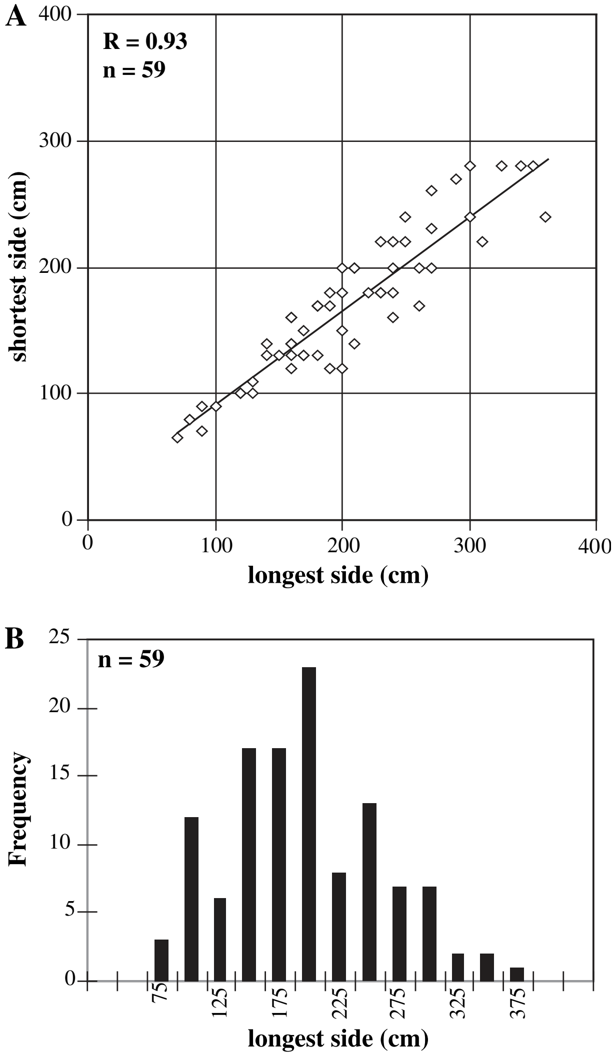


**Fig. 6.** Statistics of buildup dimensions in the lower interval. (A) Plot of longest vs. shortest buildup sides at site D-026. Correlation coefficient of 0·93 points to a systematical relationship between longest and shortest buildup sides. (B) Histogram of frequency distribution of longest buildup sides. Buildup data were sorted in 16 groups ranging from 25 to 400 cm.

The buildup-encasing facies consists of chalky and coarse, whitish to ochre grainstones, rudstones, and floatstones and is not much different from the buildup facies. A main difference is that the buildups are often structureless, whereas the encasing facies shows well-developed cross-bedding (Fig. 5D). The large-scale cross-bedding points to a high-energy setting with subaquatic dunes having crest heights in excess of one metre. The biota of the dune rudstones consists of *Lithocodium-Bacinella* lumps (1–5 cm in size), peloids, fragmented, transported and re-deposited rudist and oyster shells, some gastropods and echinoderms, green algae, and rare orbitolinid and biserial foraminifera.

### *Number of buildups per unit area*

The outcrops exposing the lower buildup level occur in a belt approximately 100 km long (north–south) and 20 km wide (east–west), i.e. an area of roughly 2000 km$^2$ (Figs 1, 3 and 4; Immenhauser *et al.*, 2004). Given the very low dip of the strata, the lower buildup level is subhorizontally exposed in desert plains and stratigraphically in small, low-relief hills (Fig. 5A–C). Portions of two buildup exposure areas in the southern field area (Wadi Baw; Fig. 1C) were mapped in detail (Fig. 7). From these maps and other exposure areas in the northern field area, the number of buildups per surface unit can be estimated. Coalescent buildups were separated and counted as two or more individual buildups. In the mapped areas, between 5 and 10 buildups with variable dimensions are present per unit area of 10 × 10 m. In three larger unit areas of 100 × 100 m, the number of buildups varied between 600 and 900.

Given that 'sediment buildups' of the lower interval are present in all exposures of this stratigraphic level in both study areas (Fig. 1), it is assumed that wide portions of the Oman shallow marine carbonate seafloor were covered by these features. Judging from the accessible exposure belts of the Qishn Formation and the average buildup density, 120–180 million buildups might have existed in this area alone.

### *Interpretation*

The common coarse grains and the porous and chalky facies limit the recognition and interpretation of the sediment-binding organisms (see Riding, 2000). Nevertheless, the presence of a wavy, microlaminated fabric (Fig. 8A), and the early marine lithification of the buildups points to a binding-trapping algal-microbial community, perhaps similar to that of coarse-grained, agglutinating thrombolites (Riding, 2000). The nodular and wavy nature of these laminae, which appear to trap small *Lithocodium-Bacinella* lumps and larger bioclasts (Fig. 8A), is distinct from mechanically formed low-angle ripple foresets.

In modern stromatolites, binding-trapping is performed by a surface community consisting of the filamentous cyanobacteria. These mucilaginous sheets trap and bind fine carbonate grains during periods of rapid stromatolite accretion. The Bahamian stromatolites are consequently composed of laminated fine ooidal carbonate

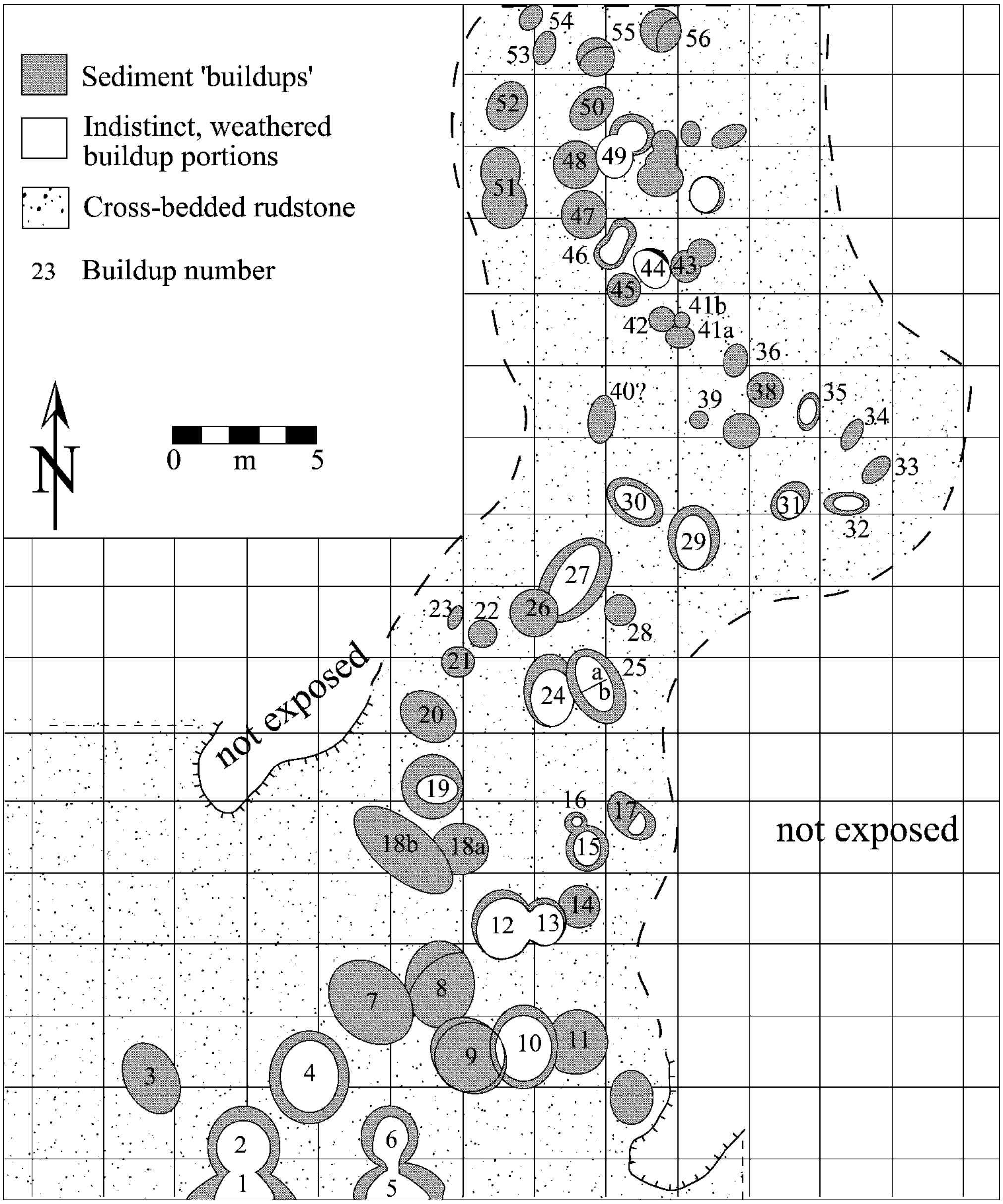


**Fig. 7.** Map of portions of exposures of the lower buildup level near section D-028 with indications of sample locations. Grid has 2·5 m spacing.

arenites (Reid & Browne, 1991). In contrast, the Oman buildups are generally built by much coarser sediment although patches and pockets of finer-grained carbonates are locally present. The scarcity of stromatolitic laminae in the Oman buildups is thus perhaps at least in part related to the overall lack of finer grains in the depositional environment (Fig. 8A).

An interesting aspect is the field evidence for early marine lithification perhaps under the influence of a dominant current direction. This is suggested by the north–south orientation of the long axis of most buildups (Fig. 7) in the three major exposure areas within the study area. Sediment accretion, combined with wave and current energy resulted in the characteristic head-shaped morphology of these features (Figs 5A–C and 7). Evidence for early marine lithification includes the following observations. The buildups maintained a stable, wave-resistant framework in a high-energy environment dominated by submarine dunes. Cross-bedded dune deposits locally underlie these features (Fig. 5B) and they form the encasing facies but they do not erode or truncate the buildups. The buildups also represent the only sites where rudist bivalves are

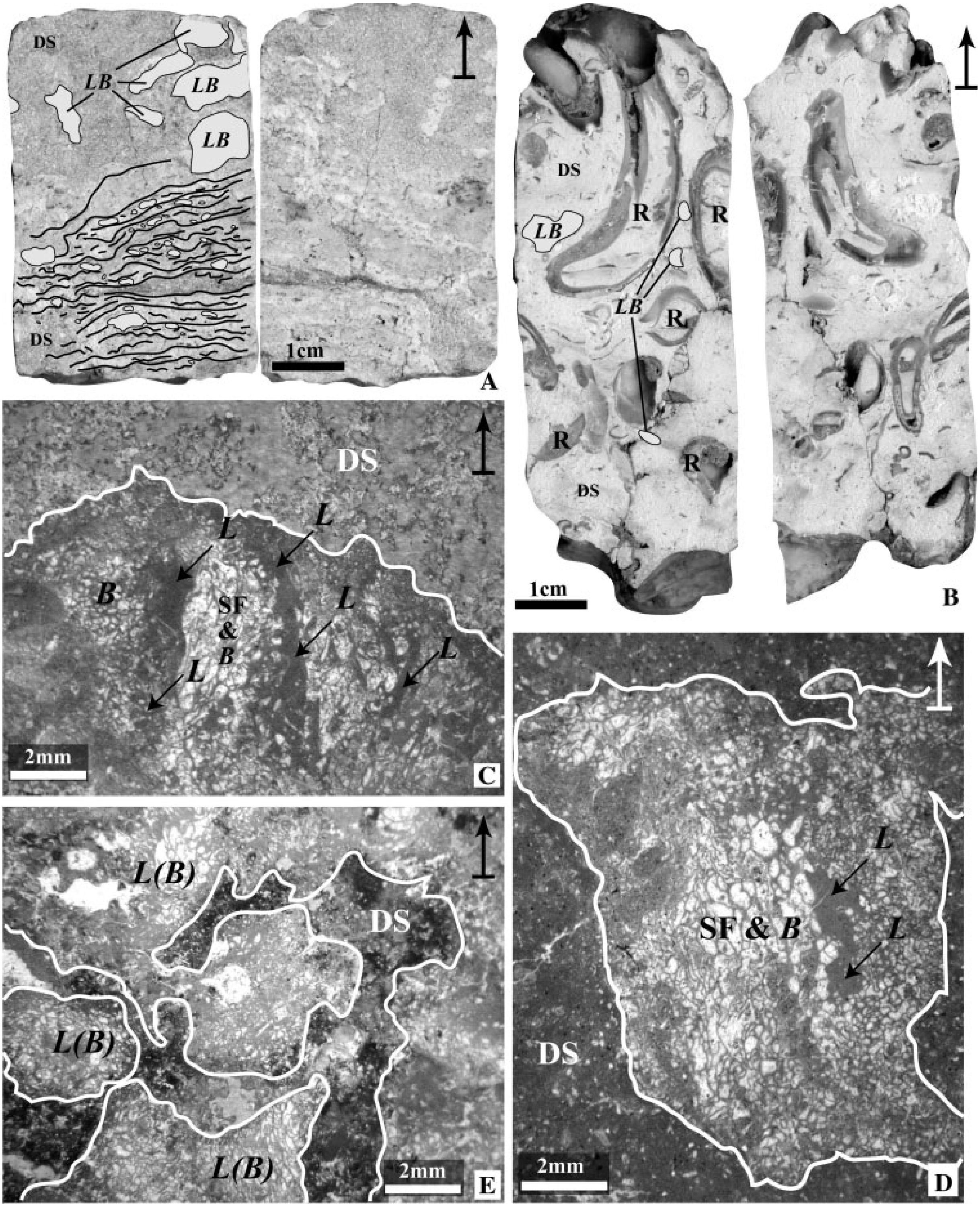


**Fig. 8.** Buildup microfacies. (A) Lower buildup interval. Two corresponding sides of longitudinally cut drill plug. On the left side, crude microbial lamination and structureless detrital sediment (DS) with *Lithocodium-Baccinella* lumps (*LB)* is traced for better visibility. (B) Lower buildup interval. Two corresponding sides of longitudinally cut drill plug. Note structureless detrital sediment (DS) with rare *Lithocodium-Baccinella* lumps (*LB)* and frequent rudist bivalves (R) in growth position. (C and D) *Lithocodium-Baccinella* facies of upper buildup interval. Note sharp boundaries of *Lithocodium-Baccinella* lumps with detrital sedimentary rock (DS). Sessile foraminifera (SF) and *B. irregularis* (*B*) within thallial cavities of *L. aggregatum* (*L*). (E) *Lithocodium-Baccinella* bindstone of the upper buildup facies.

frequently found intact and in growth position pointing to a solid substratum. In contrast, rudist bivalves in the buildup-encasing dune facies are always fragmented and transported.

## Upper (*Lithocodium-Bacinella*) buildup interval

### *Buildup dimensions, shape and facies*

The *Lithocodium-Bacinella* buildups of the upper interval are mostly isolated, morphologically complex structures, approximately 2–4 m wide and 0·5–1·5 m in height (Fig. 5F). They have steep flanks (45° to vertical) from which a few cm-thick and a few dm-long aprons of *Lithocodium-Bacinella* lumps descend. The size of the individual lumps varies considerably but their longest dimension is generally 1–2 cm. The buildups have planar to irregular, digitate boundaries and interfinger laterally (or change gradually) with (into) the encasing sedimentary rocks (Fig. 5F). Locally, the uppermost portions of the buildups prograde laterally and form table-like morphologies (Fig. 5F). In the two-dimensional exposures of this interval, buildups are laterally separated by about 1·2–1·6 m of coarse bioclastic rudstone or floatstone commonly with dm-scale dune foresets. In some places, the *Lithocodium-Bacinella* buildups are easily distinguished from the surrounding sedimentary rocks by their brownish colour, the result of facies-selective early Holocene dolomitization (Fig. 5F; Immenhauser *et al.*, 2004).

The fabric of *Lithocodium-Bacinella* (Fig. 8C and D) buildups is thrombolitic and inhomogeneous, mostly nodular or knobby. Some buildups contain three or more conspicuous, laminated to nodular *Lithocodium-Bacinella* 'layers' several centimetres in thickness. A main characteristic of these buildups is that they are predominantly built by the *Lithocodium-Bacinella* consortium (as opposed to the 'sediment' buildups of the lower interval). In thin sections, *L. aggregatum* dominates, whereas *B. irregularis* is subordinate (Fig. 8C and D).

At the base of the upper buildup interval, an ~ 0·5–1 m-thick, massive succession of laterally coalescent *Lithocodium-Bacinella* lumps (one to several cm in size) covers the ancient carbonate seafloor (Fig. 5E). In the southern study area (Wadi Baw; Fig. 1), these massive layers are correlatable across several tens of kilometres.

The buildup-encasing sedimentary rocks consist of whitish–yellowish medium to coarse-grained packstone, grainstone, rudstone or floatstone. The grainy facies displays a prominent cross-bedding pointing to approximately one metre high subaquatic dunes (Fig. 5D and F). Irregular *Lithocodium-Bacinella* lumps as well as peloids are abundant to dominant in the floatstone facies. This biota furthermore includes miliolid foraminifera, green algae, bivalves, rare orbitolinid foraminifera, spiculae, and very rare rudist and oyster shell fragments. *Lithocodium-Bacinella* lumps and oncoids line up to mimic the morphology of submarine dunes. Metre-scale, flat and irregularly shaped *Lithocodium-Bacinella* patches are common features (Fig. 5D).

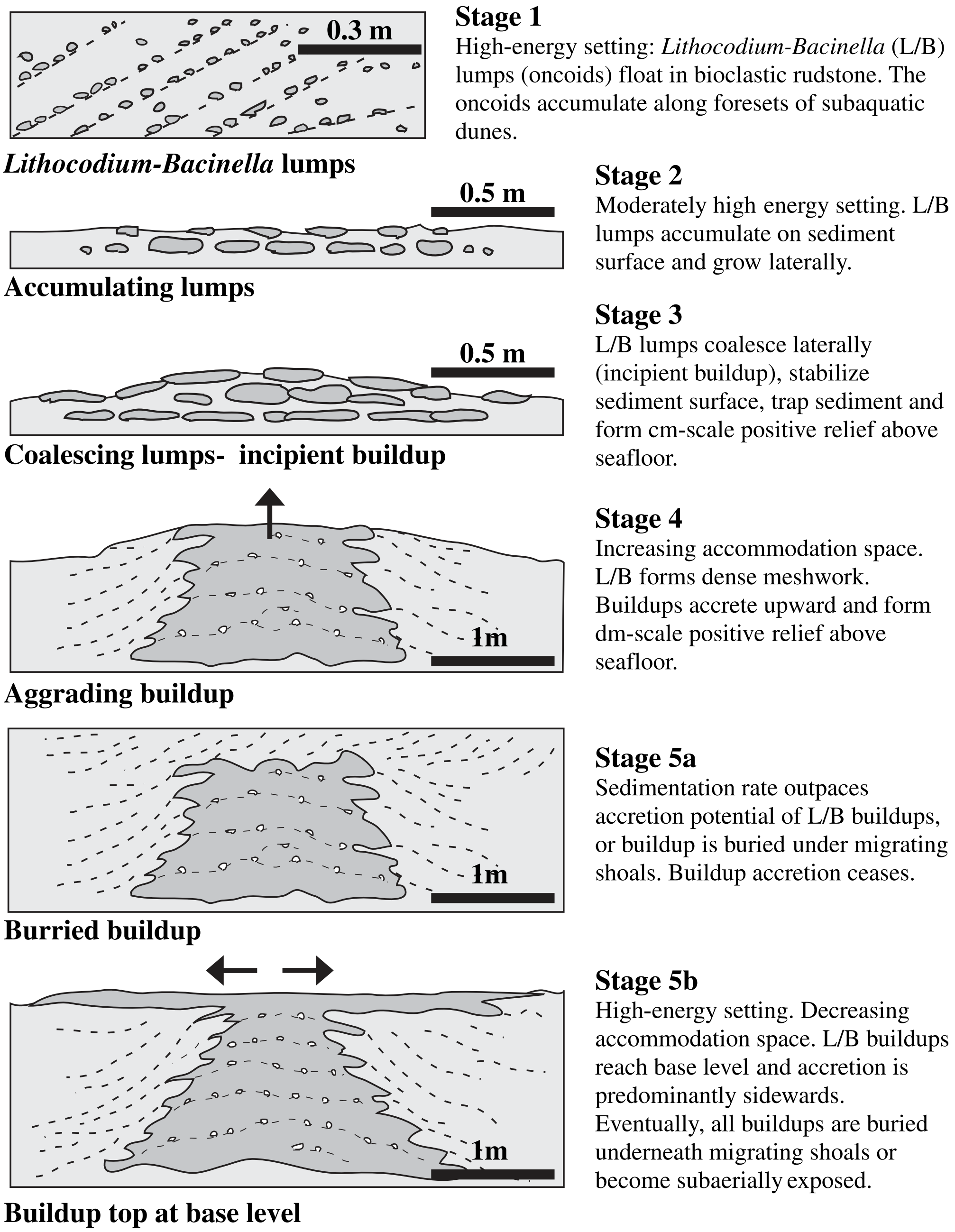
### *Number of buildups per unit area*

Due to the two-dimensional outcrops of the upper buildup level (Fig. 5F), the number of buildups per surface unit area cannot be estimated. Generally, they are wider (2–4 m) and higher (0·5–1·5 m) than the buildups of the lower interval (1·5–2 m wide and 0·2–0·5 m high), more widely spaced (0·5–5 m; Fig. 9) and might have been a more local feature extending over a few tens to a few hundreds of km$^2$. Nevertheless, this assumption is perhaps biased by the exposure conditions and by the observation that the *Lithocodium-Bacinella* floatstone facies extends beyond the geographical area characterized by these buildups (Fig. 4).

### *Interpretation*

Similar to the buildups of the lower interval, field evidence clearly points to early marine lithification of *Lithocodium-Bacinella* buildups. In this context, the presence of small aprons built by cm-sized *Lithocodium-Bacinella* lumps is significant (Fig. 5F). This indicates that these features formed positive structures rising above the seafloor. Additional field evidence for an early marine rigidity are erosional pockets within individual buildups that are filled with graded bioclastic carbonates.

*Lithocodium-Bacinella* buildups of the upper interval display a characteristic evolution beginning with coalescing lumps and extending to metre-high, morphologically complex pinnacles that interfinger with the surrounding sand waves. Calcified chambers of *L. aggregatum* (Fig. 8D) are the main component of the buildup fabric. The morphological differences between buildups in the lower and upper interval (Figs 5 and 9) are perhaps related to the different buildup consortia. Other factors that might affect buildup morphologies include environ-



**Stage 1**
High-energy setting: *Lithocodium-Bacinella* (L/B) lumps (oncoids) float in bioclastic rudstone. The oncoids accumulate along foresets of subaquatic dunes.

**Stage 2**
Moderately high energy setting. L/B lumps accumulate on sediment surface and grow laterally.

**Stage 3**
L/B lumps coalesce laterally (incipient buildup), stabilize sediment surface, trap sediment and form cm-scale positive relief above seafloor.

**Stage 4**
Increasing accommodation space. L/B forms dense meshwork. Buildups accrete upward and form dm-scale positive relief above seafloor.

**Stage 5a**
Sedimentation rate outpaces accretion potential of L/B buildups, or buildup is buried under migrating shoals. Buildup accretion ceases.

**Stage 5b**
High-energy setting. Decreasing accommodation space. L/B buildups reach base level and accretion is predominantly sidewards. Eventually, all buildups are buried underneath migrating shoals or become subaerially exposed.

**Fig. 9.** Schematic illustration of six time-slices in the evolution of *Lithocodium-Baccinella* buildups in the upper interval (section view). Stage 1, *Lithocodium-Baccinella* lumps, and stage 5b, fully developed buildup at base level, are end members. All stages coexist in outcrops. Eventually all buildups were buried under subaquatic dunes and buildup accretion ceased.

mental conditions such as water depth, hydrodynamic level, salinity and trophic level. However, the significance of these external factors, is difficult to assess because the *Lithocodium-Bacinella* consortium is extremely versatile and present in a wide range of marine depositional environments (Immenhauser *et al.*, 2001; Hillgärtner *et al.*, 2003).

## CHRONOSTRATIGRAPHY OF BUILDUP INTERVALS

In order to pinpoint the age of the buildup intervals, a combined biostratigraphic-chemostratigraphic approach was chosen. The biostratigraphy of the Qishn Formation is documented in detail in Immenhauser *et al.* (2004) but the temporal resolution of most fossils in these shallow-water sections is limited. Nevertheless, based on the rudists *Offneria nicolinae* and *Offneria* cf. *murgensis*, Sequence IV of the Qishn Formation, containing the two buildup intervals, is indisputably Lower Aptian in age (Fig. 2; Immenhauser *et al.*, 2004). These considerations formed the foundation for the chemostratigraphic approach.

A steep gradient in $^{87}Sr/^{86}Sr$ values of Cretaceous seawater from the Late Barremian to the Late Aptian allows precise stratigraphic correlation within this interval (McArthur *et al.*, 2001). In addition, the global carbon isotope record of the Early Aptian is particularly characteristic and well studied (e.g. Erbacher *et al.*, 1996; Menegatti *et al.*, 1998; Weissert *et al.*, 1998; Jenkyns & Wilson, 1999). Based on strontium isotope ratios of low-Mg calcitic rudists in several of the Qishn Formation sections (Immenhauser *et al.*, 2004) and applying the high-resolution $\delta^{13}C$ stratigraphy of the Alpine Tethys (Menegatti *et al.*, 1998), it is proposed that the two buildup intervals in Oman are coeval with the Selli event of Wetzel (1985), i.e. the Oceanic Anoxic Event 1a of Arthur *et al.* (1990; Fig. 10).

Menegatti *et al.* (1998) divided the Cismon $\delta^{13}C$ stratigraphy into eight segments (C1–C8). This $\delta^{13}C_{carb}$ chemostratigraphy of OAE 1a is characterized by a stable interval (C5) and preceded and followed by abrupt, step-like shifts to more positive values (C4 and C6). Menegatti *et al.* (1998) identified the same pattern in the Early Aptian $\delta^{13}C_{carb}$ record of Oman (Vahrenkamp, 1996). Applying this chemostratigraphic pattern to the Qishn Formation $\delta^{13}C_{carb}$ stratigraphy, the lower buildup interval is perhaps contained in the C5 segment whereas the upper buildup interval seems to coincide with portions of the C6 segment (Fig. 10).

Strontium isotope ratios (Immenhauser *et al.*, 2004) allow for an approximate estimate of 2 cm/1000 yr as the mean sediment accumulation rate for the Qishn Formation. This value is very similar to the 1·84 cm/1000 yr for Albian platform facies in northern Oman (Immenhauser & Scott, 2002). This rather low value is not surprising considering that the study area is on the proximal shoulder of the Haushi-Huqf High, which would account for low accommodation. Both buildup layers are approximately 3 m in thickness (Fig. 4). Applying the sedimentation rate of 2 cm/1000 yr, a duration of about 150 kyr is estimated for each interval.

## TAXONOMIC RELATIONSHIPS OF *LITHOCODIUM AGGREGATUM* ELLIOTT AND *BACINELLA IRREGULARIS* RADOIČIĆ

*Lithocodium aggregatum* and *Bacinella irregularis* were widespread in Mesozoic shallow marine seas. The taxonomic relationship of these now extinct organisms, however, is the subject of an ongoing debate. *Lithocodium aggregatum* was first described by Elliott from the Hauterivian of Iraq (Elliott, 1956) and classified as a codiacean alga. Subsequently, Radoičić described *Bacinella irregularis* from carbonates of Barremian-Aptian age in the Yugoslav Dinarides (Radoičić, 1972) and classified them as algae *incertae sedis*, possibly belonging to the Codiacea.

It has been suggested that *L. aggregatum, Pseudolithocodium carphathicum* and *B. irregularis* represent different ontogenetic stages of the same organism (Segonzac & Marin, 1972; Banner *et al.*, 1990). Masse (1976) argued that these microfossils were of multiple (symbiotic) botanical origin. Furthermore, Banner *et al.* (1990) proposed that *L. aggregatum* Elliott is the senior synonym for all such forms. Shortly thereafter, *L. aggregatum* was (re-)classified as a calcifying cyanobacterium (Riding, 1991a). Most recently, Schmid & Leinfelder (1995, 1996) have argued that *L. aggregatum* represents the adult growth form of the lofusiid foraminifer *Troglotella incrustans*. *Bacinella irregularis* is now commonly interpreted as a calcifying cyanobacterium (Camoin & Maurin, 1988; Riding, 1991b; Schmid & Leinfelder, 1996).

Although it is not the intent of this study to contribute to the discussion of *Lithocodium-Bacinella* taxonomy, *L. aggregatum* and *B. irregularis* are recognizable structures independent of their taxonomic relationship (see Discussion in Leinfelder *et al.*, 1993). In addition, the Oman buildups demonstrate that *Lithocodium-Bacinella* functioned as trappers, binders and framework formers.

Where identified in thin sections (Fig. 8C and D), the interpretation of *L. aggregatum* as a sessile larger foraminifera (Schmid & Leinfelder, 1995, 1996) that possibly lived as a symbiont or parasite in the (codiacean?) algal tissue is accepted as a working hypothesis. Nevertheless, these authors based their interpretations mainly on Jurassic material and just mentioned the presence of *Bacinella* in the basal cavities of *Lithocodium* in a Cretaceous specimen. In the Aptian material from Oman, both coelobithic foraminifera and

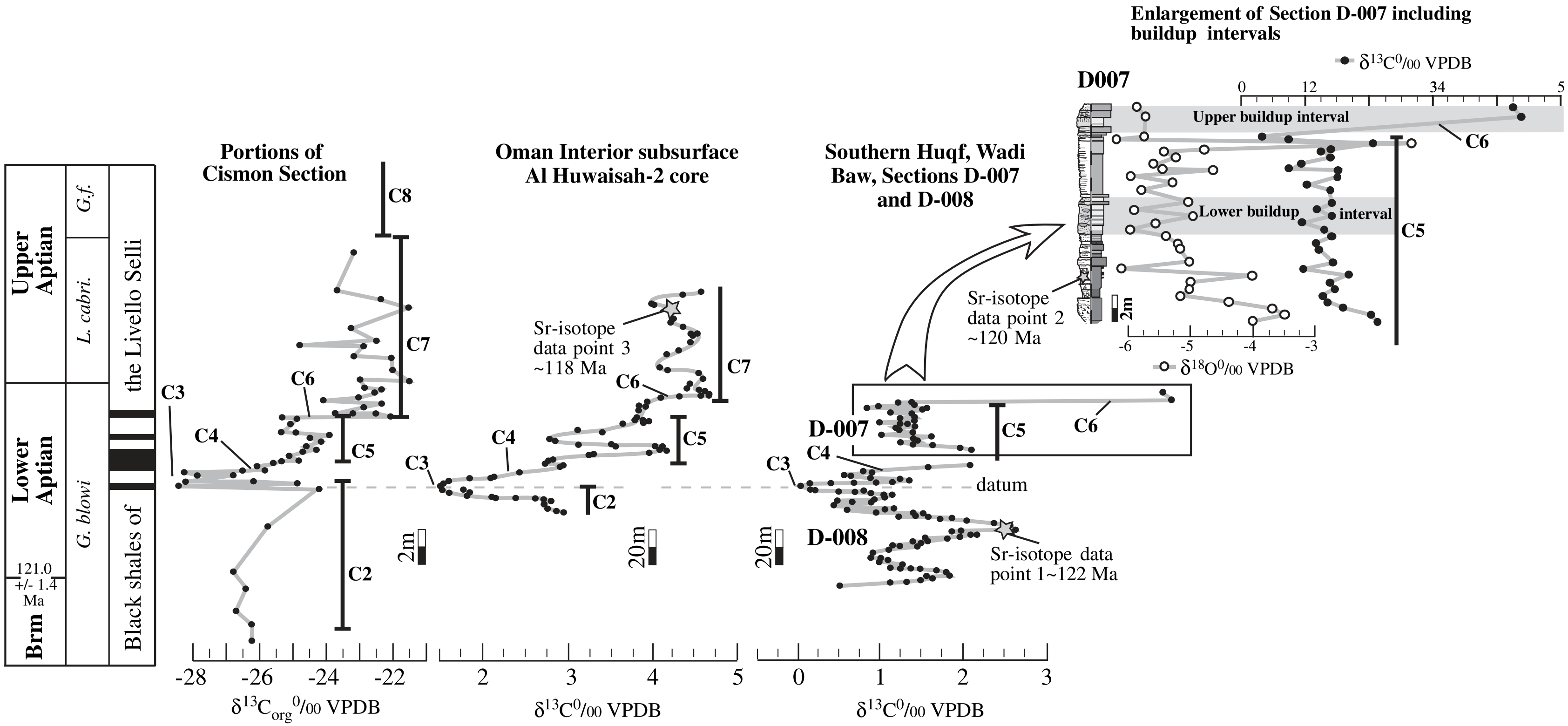


**Fig. 10.** Chemostratigraphy of sections D-008 and D-007 (southern field area, Wadi Baw) in comparison with basinal section (Shu'aiba Formation, Vahrenkamp, 1996) and the Cismon section (Menegatti *et al.*, 1998). In order to correlate sections, Sr data (Immenhauser *et al.*, 2004) and the high-resolution $\delta^{13}C$ stratigraphy of Menegatti *et al.* (1998) were applied. The Cismon $\delta^{13}C_{org}$ curve is chosen for higher resolution. C2 to C8 refer to the chemostratigraphic segments of Menegatti *et al.* (1998). The Selli event is contained in segments C4 through C6. The lower buildup interval falls within the segment C5 of the Selli event and the upper buildup interval coincides with segment C6. The planktonic foraminifera stratigraphy is after Erba *et al.* (1999) and Sr-chemostratigraphy 'ages' are derived according to Gradstein *et al.* (1994).

*Bacinella* are recognised. Where indistinct, or where *L. aggregatum* and *B. irregularis* co-existed, the label '*Lithocodium-Bacinella*' is used as a descriptive term following previous workers (e.g. Dupraz & Strasser, 1999). *Lithocodium-Bacinella* includes calcifying (cyano)bacteria, sessile foraminifera, algae and other microorganisms contributing to these buildups.

## GEOGRAPHIC AND STRATIGRAPHIC DISTRIBUTION OF MICROBIAL AND *LITHOCODIUM-BACINELLA* FACIES

In Arabia, *Lithocodium-Bacinella* facies is not limited to the Early Aptian. In Wadi Mu'aydin, about 350 km to the north of the study area (WM in Fig. 1B), *Lithocodium-Bacinella* is described from Valanginian through Aptian carbonates, whereas it appears to be absent in Albian and younger rocks (Simmons & Hart, 1987). It is thus not the occurrence of *Lithocodium-Bacinella per se* that makes the Early Aptian remarkable, but rather the widespread occurrence in buildups and massive bindstone facies.

The area in which the *Lithocodium-Bacinella* buildup interval (Fig. 4) and the massive *Lithocodium-Bacinella* bindstone level (Fig. 5E) crop out is limited to the southern field area (Wadi Baw; Fig. 1C). Buildup structures are exposed in low-relief hills distributed east–west across the Wadi Baw study area; the buildup facies is laterally replaced by a *Lithocodium-Bacinella* floatstone (Figs 4 and 8). The continuation of the *Lithocodium-Bacinella* facies as such, while the buildups disappear, might be an environmental feature (e.g. hydrodynamic level or water depth). This indicates that *Lithocodium-Bacinella* extended over a much wider area than that delimited by the buildup facies.

With reference to other Early Aptian occurrences in eastern Arabia, two *Lithocodium-Bacinella* 'oncoid' intervals, between 3 and 12 m in thickness, are present at Jabal Madar about 250 km north of the Wadi Jarrah study area (JM in Fig. 1B; van Buchem *et al.*, 2002). *Lithocodium-Bacinella* facies associated with corals, rudists, foraminifera, bryozoans, red algae, sponges, serpulids and microbial limestones is recognized in many Lower Aptian sections across the northern Oman Mountains (Simmons & Hart, 1987; Masse *et al.*, 1997; Immenhauser *et al.*, 2001; Pittet *et al.*, 2002; Hillgärtner *et al.*, 2003) as well as in exposures and in the subsurface of the United Arab Emirates, Saudi Arabia and the Arabian Gulf (Figs 1B and 3; Alsharhan, 1985, 1987; Hughes, 2000; van Buchem *et al.*, 2002). Moreover, a Lower Aptian massive bioconstructed platform rim containing abundant *Lithocodium-Bacinella*-dominated buildup structures was described from Northern Oman (Wadi Baraka; WB in Fig. 1B; Hillgärtner *et al.*, 2003). A regional overview of well-documented Lower Aptian sections with *Lithocodium-Bacinella* facies in eastern Arabia is shown in Fig. 3.

Lower Aptian *Lithocodium-Bacinella* facies, however, also occurs outside of Arabia. A prominent example illustrating its wide geographical range is the north-west Pacific Takuyo-Daisan Guyot (Aptian-Albian), cored during Ocean Drilling Program Leg 143 (Sager *et al.*, 1993). The *Lithocodium-Bacinella* 'oncoidal' floatstones at the perimeter of this seamount are quite comparable to the facies present in the uppermost slope facies in Wadi El Assyi (Immenhauser *et al.*, 2001). *Lithocodium-Bacinella* bindstones are known from the Early Aptian of Spain, Croatia, Southern Italy and Portugal. Moreover, *Lithocodium-Bacinella* is present in the mid-Cretaceous Cupido Formation surrounding the Gulf of Mexico (Lehmann *et al.*, 1999). These examples represent productive shallow-marine carbonate systems in contrast to the Early Aptian drowning episodes recorded by Tethyan carbonate platforms elsewhere (e.g. Schlager, 1981; Masse & Philip, 1981; Föllmi *et al.*, 1994; Weissert *et al.*, 1998; Jenkyns & Wilson, 1999).

Given these considerations, it seems likely that the Early Aptian *Lithocodium-Bacinella* facies is a Tethys-wide feature. However, a comparable high-resolution stratigraphic framework is lacking for other localities. Therefore, improvement of the temporal resolution and geographic correlation of this particular facies should be the focus of future research.

## DISCUSSION

### Stratigraphic distribution of biota in Sequence IV

The biota in the upper portions of Sequence IV, including the two buildup intervals (Fig. 4), is organized in a systematic pattern (Fig. 11). The buildup intervals are generally characterized by a low abundance (or absence) of rudist bivalves and their debris. Some of the sediment buildups

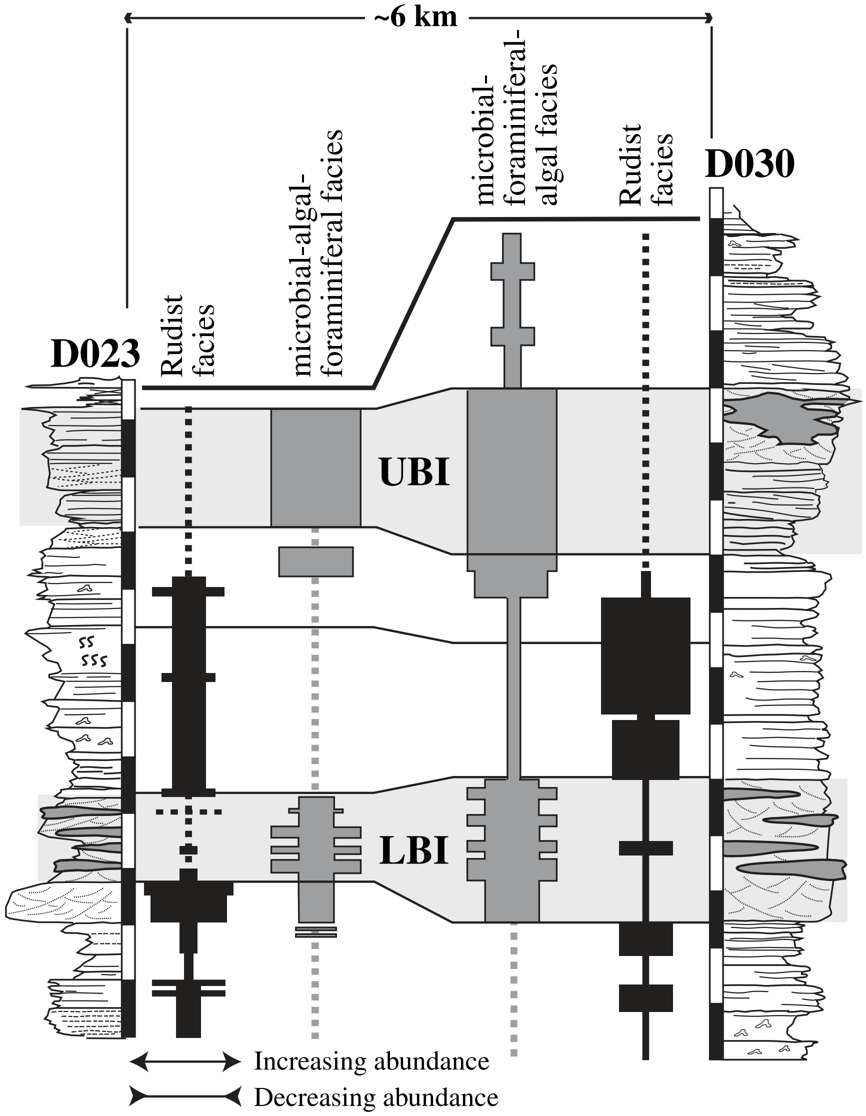


**Fig. 11.** Comparison of semiquantitative estimates of rudist shell abundances vs. microbial and *Lithocodium-Baccinella* facies in two sections (relative scale). Widest bars indicate 'volumetrically dominant' and stippled lines indicate 'present but rare'. LBI = lower buildup interval; UBI = upper buildup interval.

of the lower interval, however, act as a stable substratum for rudists and locally rudist bivalves are volumetrically more significant (Fig. 8B). Rudists or their shell fragments are absent from the massive bindstone and buildup facies of the upper *Lithocodium/Bacinella* interval (Fig. 11). This sudden disappearance of the rudist bivalves is evidence for the establishment of an out-of-balance community structure as represented by the *Lithocodium/Bacinella* consortium.

In contrast, rudist bivalves are by far the most dominant skeletal components in beds underneath and above the buildup intervals (Figs 4 and 11). Miliolid and orbitolinid foraminifera, variable abundances of oysters and gastropod shell debris, echinoderms and green algae are present in all 16 sections measured throughout Sequence IV, including the buildup levels.

This characteristic biotic pattern of rudist bivalves alternating with *Lithocodium/Baccinella* and related organisms, is also known from Lower Aptian lagoonal limestones of the Delphino Helvetic realm (Trabold, 1996). There, foraminiferal-algal, *Bacinella*, and *Girvanella* oncoids (microfacies type 14 of Trabold, 1996) alternate stratigraphically with rudist buildups and their debris (microfacies type 15 of Trabold, 1996). It is thus suggested that this biotic pattern is a characteristic and significant feature of these Lower Aptian shoalwater limestones.

## Hypotheses for the short-lived expansion of out-of-balance facies in Oman

In order to evaluate the transient occurrence of an out-of-balance facies in the Aptian of Oman, three working hypotheses are considered.

### *Stressed refugia hypothesis*

The rise of grazing metazoans has long been considered responsible for the long-term decline of stromatolites after their Precambrian dominance (e.g. Garrett, 1970; Awramik, 1971; Riding, 2000). Is it conceivable that the Oman buildups occupied stressed refuges that were hostile to both grazers and rudist bivalves? Probably not. The presence of large gastropods and echinoderms suggest that a temporal absence of grazing metazoans was not the controlling factor for the Oman buildup expansion. Furthermore, the normal marine fauna and sedimentologic evidence for high levels of hydrodynamic energy point to normal seawater salinity in a well-oxygenated environment.

### *Post-disaster biota hypothesis*

Schubert & Bottjer (1992) argued that the increased abundance of stromatolite consortia immediately after the Permian–Triassic boundary was a response to the mass extinction of competitive organisms. Schlager (2003) offered a similar explanation for microbial dominance after the Late Devonian extinction. This hypothesis might be in line with the Early Aptian period of floral and faunal change (Erba, 1994; Erbacher *et al.*, 1996; Leckie *et al.*, 2002 and references therein) or platform drowning elsewhere in the Tethyan realm (e.g. Weissert *et al.*, 1998). Judging from the normal marine biota (including echinoderms) within these rocks, however, the notion of a post-disaster biota is not a valid explanation for this out-of-balance facies. Moreover, the temporal overlap with the Selli level suggests that the Oman buildups are a syn-disaster facies as opposed to a post-disaster facies.

### *Climatic factors, palaeofertility and seawater saturation state*

Hillgärtner *et al.* (2003) discussed the possible causal relationship between buildup features at the Lower Aptian oceanic margin of the Arabian plate in Wadi Baraka (Fig. 1b) and the OAE 1a event. Neuweiler and Reitner (1992) postulated alkalinity changes or eutrophic conditions for occurrences of *Lithocodium*-bindstone up to 9 m thick in the Early Albian of Spain perhaps related to the OAE1b (Niveau Pasquier). Here, this line of reasoning is explored because of the temporal coincidence of Oman carbonate buildups and the OAE1a (Fig. 10).

The debate on the controlling mechanisms of the Early Aptian basinal black shales is controversial but, in general, the deposition of this facies has been attributed to reduced organic matter re-mineralization due to oceanic anoxia or to increased primary productivity overwhelming the re-mineralization potential of the water column under oxic conditions (Schlanger & Jenkyns, 1976; Arthur *et al.*, 1990; Hochuli *et al.*, 1999). Erbacher *et al.* (1996) investigated extinction–radiation events of mid-Cretaceous radiolaria across Aptian to Cenomanian oceanic anoxic events and compared these findings against data from Rock Eval analysis of organic matter in the corresponding black shale intervals. According to Erbacher *et al.* (1996), OAE 1a coincides with an overall transgressive period and maximum flooding resulting in leaching of nutrients (mainly $NO_3$, $PO_4$ and Si) on coastal lowlands and resulting fertilization and productivity in the adjacent oceanic basin. The nutrient hypothesis is supported by the type II kerogen contained within the black shales of the Selli level, which might indicate, coupled with the subsequent positive $\delta^{13}C$ excursion, increased marine productivity based on an increased trophic level (Erbacher *et al.*, 1996).

Another point that merits discussion is seawater carbonate alkalinity and particularly seawater saturation state with respect to $CaCO_3$ (Kempe & Kazmierczak, 1993; Riding, 2000). The role of seawater carbonate alkalinity is perhaps most important in the case of the thrombolitic *Lithocodium-Bacinella* bindstone at the base of the upper interval (Fig. 5E). As discussed by previous authors (e.g. Neuweiler & Reitner, 1992; Hillgärtner *et al.*, 2003), the early marine calcification of these considerable volumes of *Lithocodium-Bacinella* demands a high seawater carbonate alkalinity. The influx of carbonate and biocarbonate anions ($CO_3^{2-}$(aq) and $HCO_3^{-}$(aq)) might in turn be related to increased weathering rates including meteoric karst formation on emergent carbonate rocks during lowstands or more humid periods.

## Lower buildup interval – comparison with modern stromatolites

Among other occurrences of modern stromatolitic communities, the Bahamian Exuma Cays stromatolites (e.g. Dravis, 1983; Reid *et al.*, 1995; MacIntyre *et al.*, 2000) and the Hamlin Pool stromatolites in Australia (e.g. Logan & Cebulski, 1970; Playford, 1990; Reid *et al.*, 2003, and many others) might provide, in some aspects, modern analogues for the Oman examples. Although the sediment buildups in the lower stratigraphic interval are not referred to as 'stromatolites', the morphology and fabric of these features share similarities with Bahamian and Hamlin Pool subtidal stromatolites.

Bahamian stromatolites are present in normal marine conditions in high energy subtidal channels, sandy subtidal embayments and intertidal beaches (Reid *et al.*, 1995). According to Reid *et al.* (1995), current velocities in these channels (up to 10 m deep) reach up to 150 cm/s. Judging from the fossil record, these parameters are comparable to those during the Early Aptian buildup episodes. Most of the Bahamian subtidal stromatolites are 0·5–1 m high (Reid *et al.*, 1995) and morphologically similar to the Oman buildups in the lower interval (Fig. 5C). In the Exuma Cays, living gastropods and other grazing metazoans, such as urchins and chitons, are abundant on the subtidal coralgal reef nearby but were not observed on the stromatolites (Reid & Browne, 1991). This implies that the presence of grazing organisms is not a limiting factor for the Bahamian stromatolites. One reason for this might be that rapid cementation is critical for stromatolite/buildup accretion greatly reducing the potential effect of burrowers and grazers (Reid & Browne, 1991). This observation is in line with the fossil biota from the Aptian of Wadi el Assyi (Fig. 1B) that is locally characterized by leiolitic and thrombolitic microbial and *Lithocodium/Bacinella* facies, abundant large gastropods and echinoderms in the same stratigraphic interval (Immenhauser *et al.*, 2001; Pittet *et al.*, 2002; Hillgärtner *et al.*, 2003).

Hamlin Pool stromatolites occur over ~100 km of shoreline to water depths of 3–4 m (Logan & Cebulski, 1970). The seawater salinity in Hamlin Pool ranges from 55‰ to 70‰ throughout the year (Reid *et al.*, 2003) and the stromatolites are believed to have developed because of these elevated salinities (i.e. the resulting absence of grazers). In this respect, and perhaps also in view of the lower hydrodynamic level, the Hamlin Pool environmental parameters are thus less comparable with the Aptian setting in Oman. Comparing growth morphologies and internal structure, the subtidal colloform-mat stromatolites (Playford, 1990) in Hamlin Pool share similarities with the Oman examples, in particular with respect to their weakly laminated, irregular growth forms including coarse fenestrae. Nevertheless, active, colloform-mats of these modern stromatolites are of a soft, coherent nature whereas subtidal stromatolites with hard surfaces were considered to be inactive (Reid *et al.*, 2003). In contrast, the Oman buildups of the lower level show ample evidence for early marine lithification.

Pending further research, this might imply that the Bahamian stromatolites are perhaps better analogues for the Oman examples due to the normal marine salinity, the high hydrodynamic level of their depositional environment and given their early marine lithified nature.

The microbial consortia that build modern stromatolites are the focus of intense research (Visscher *et al.*, 1998). In general, microbial mats are highly complex and dynamic ecosystems typified by steep chemical gradients across only millimetres creating distinct intramat microenvironments. These microbial ecosystems are characterized by coupled biogeochemical reactions including a wide range of metabolic processes (Visscher *et al.*, 1998). The complex interactions of oxygenic phototrophs, aerobic heterotrophic bacteria, sulphate-reducing bacteria, and sulphide-oxidizing bacteria makes the comparison of these modern microbial ecosystems to what might perhaps be fossil analogues difficult. Nevertheless, it seems to be a fundamental pattern of such microbial communities to use dissolved organic carbon or, alternatively, dissolved inorganic compounds, when for example oxidizing sulphide with oxygen to generate energy, while fixing carbon dioxide for use as cell material (e.g. Visscher *et al.*, 1998).

## Upper buildup interval – comparison of *Lithocodium* with sessile, larger foraminifera

According to Schmid & Leinfelder (1995, 1996) *L. aggregatum* represents the adult growth form of the lofusiid foraminifer *T. incrustans*, an extinct larger sessile foraminifera, in the basal cavity of what might be a green algae. In this sense, the Oman *Lithocodium*-dominated buildups can be referred to as 'algal-foraminiferal reefs'. Although larger benthic foraminifera are abundant in modern scleractinian reefs, recent examples of foraminifera reefs are unknown to science. Nevertheless, it has been suggested that some recent larger sessile foraminifera have the 'potential' to form reef-like carbonate bodies given favourable conditions. The metabolism of modern larger sessile foraminifera might differ in some aspects from that of *L. aggregatum*. In general, however, many fossil larger foraminifera show morphological features that are quite comparable to those of their modern counterparts and it is likely that fundamental similarities exist.

One of the largest, recent sessile foraminifera is *Acervulina inhaerens* of which the adult shells encrust surfaces of over 50 $cm^2$. A significant feature of these organisms is that they lack photosynthetic symbionts and rhizodopods, characteristic features of vagile larger foraminifera (Reiss & Hottinger, 1984). Furthermore, in the present-day Red Sea, the depth distribution of these organisms is strictly limited to the comparably nutrient-rich, deeper water levels (40–130 m) where they compete with red algae. In contrast, these organisms are absent in the oligotrophic surface waters, the site of modern scleractinian reefs. It has been documented that *A. inhaerens* predominantly feeds on benthic diatoms (Reiss & Hottinger, 1984) but otherwise accepts any type of organic particles and prefers at least mesotrophic levels. These features and particularly the inferred absence of photosynthetic symbionts are significant in this context inasmuch as this is in agreement with the notion of an elevated Early Aptian seawater palaeofertility.

## Palaeoecology of rudist bivalves

Modern shallow marine reefal ecosystems are very much affected by changes in seawater temperature and trophic levels (e.g. Hallock & Schlager, 1986; McCulloch *et al.*, 2003 and references therein). Because nutrients ($PO_4$, $NO_3$, Si) are rapidly taken up by phytoplankton and benthic algae, dissolved-nutrient levels are generally low in sea-surface waters unless the input exceeds the recycling capacity. As a consequence, scleractinian coral reefs are adapted to low-nutrient conditions (Mutti & Hallock, 2003).

In contrast, most Cretaceous rudists probably did not have a symbiotic relationship with photosynthetic algae and, in contrast to scleractinian corals, thrived in muddy waters and under elevated nutrient levels (Ross & Skelton, 1993; Scott, 1995; Skelton *et al.*, 1997; Johnson *et al.*, 2001). The widely accepted assumption is that rudists filter-fed on organic matter particles and phytoplankton that flourished under mesotropic conditions (Johnson *et al.*, 2001; Mutti & Hallock, 2003) but different rudist species might have had different tolerance limits. The abundance of rudist bivalves in the Early Aptian of Oman further supports an elevated seawater nutrient level above the tolerance level of scleractinian corals (see Discussion in Mutti & Hallock, 2003).

## Shoalwater biotic evidence for an OAE1a nutrient model?

In order to explore the possible relationships between Early Aptian seawater fertility and buildup consortia, the metabolism and the nutrient dependency of microbial consortia, larger sessile foraminifera and rudist bivalves must be considered. Although comparative studies of modern and fossil organisms are regularly carried out (e.g. Mutti & Hallock, 2003), such considerations are based on circumstantial evidence and thus must be treated with care.

The marine biota in the studied sections and the high hydrodynamic level clearly indicate oxic, normal marine conditions during buildup episodes. Hypersaline or brackish seawater, or suboxic conditions as the driving factors of buildup blooms are thus ruled out. Similarly, the notion of a calcification or carbonate alkalinity crisis is rejected. In fact, judging from field evidence, the carbonate production was high.

Based on recent analogues, however, the main fossil groups present in these Lower Aptian sections (i.e. microbial assemblages, macroalgae, larger sessile foraminifera, and rudist bivalves), all favoured elevated trophic levels but with different tolerance limits. As discussed in Mutti & Hallock (2003) the community structure of low-latitude carbonate platforms can be characterized along nutrient gradients typified by primary limiting factors. In the transition between oligotrophic and mesotrophic conditions, abundant nutrients stimulate plankton blooms limiting the availability of sunlight essential for benthic corals. Corals, although present elsewhere in the Qishn Formation (Immenhauser *et al.*, 2004), are absent in the stratigraphic interval that contains the buildup levels. In contrast, rudist bivalves that did not live in symbiotic relationship with photosynthetic algae were perhaps able to initially compete for space with macroalgae and heterotrophs that flourish under rising nutrient levels but finally declined in a stressed high-energy environment.

Assuming that the nutrient concept (Jenkyns, 1980; Erbacher *et al.*, 1996; Menegatti *et al.*, 1998; Hochuli *et al.*, 1999) is valuable, enhanced continental runoff, for instance from the Arabian craton in Saudi Arabia, or the Haushi-Huqf High (Fig. 1), might have caused nutrient-rich waters to initially move across the shallow Arabian platform before reaching the Tethyan Sea (Fig. 3).

Nevertheless, it is important to distinguish between firmly established field data and circumstantial palaeoecological evidence based on comparative studies of extinct and modern life forms. Here, the presence of the lower and upper buildup levels in Oman and their temporal correlation to the OAE 1a is considered as being well constrained (Fig. 10). In contrast, the precise temporal correlation to similar facies in other Tethyan sections requires further work. Here, the alternating foraminiferal-algal and rudist floatstone facies is considered to be a significant biotic pattern. In contrast, considerations concerning the palaeoecology of these extinct life forms and their significance for the interpretation of the Selli event are based on circumstantial evidence and must be considered as working hypotheses. Nevertheless, environmental effects and biological interactions are commonly linked (Leinfelder *et al.*, 1993; Hochuli *et al.*, 1999; Riding, 2000) supporting a mechanistic link between the presence of out-of-balance faunal and floral communities and the oceanic conditions characteristic of the OAE1 event.

## CONCLUSIONS

Two Lower Aptian intervals with microbial-algal-foraminiferal buildups and massive bindstone facies (out-of-balance communities) are present in the epicontinental platform deposits of Oman; a biota recognized across eastern Arabia. High-resolution chemostratigraphic correlation of Lower Aptian shallow-water sections suggests that these shoalwater buildup episodes were coeval with basinal black shale deposition of the Early Aptian OAE1a. This is significant because the Oman Lower Aptian sections provide the shoalwater counterpart to basinal black shale deposition.

In Oman, the stratigraphically lower interval is characterized by sediment-dominated buildups, typified by synsedimentary rigidity, with a locally stromatolitic to thrombolitic, but mostly structureless fabric. The buildups of the upper interval are morphologically complex features constructed by the problematic *Lithocodium-Bacinella* consortium.

The influence of nutrient gradients on carbonate platform community structures is considered the most likely model for the origin of the Oman buildup episodes studied here. This hypothesis for the OAE1a as a nutrient/productivity event, however, requires further study involving a larger-scale regional coverage, refined temporal resolution, and the integration of palaeofertility proxies such as Ba/Cd or Cd/Ca ratios of skeletal components from the relevant stratigraphic intervals.

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