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Sediment production and dispersal on foraminifera-dominated early Tertiary ramps: the Eocene El Garia Formation, Tunisia

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ABSTRACT

Larger benthic foraminifera *Nummulites* are common within Eocene, circum-Tethyan limestones. Despite their importance as sediment producers, contradictions in the literature constrain current understanding about the location of the *Nummulites* 'factory'. The El Garia Fm was deposited on a ramp with localized palaeohighs, and whilst some authors suggested that the locus of *Nummulites* production was in shallow water across the palaeohighs, others concluded that production was significantly reduced over these palaeohighs, and concentrated in the surrounding deeper (30–60 m) water. There are also marked dissimilarities between recent models in terms of the continuity, correlation and resolution of depositional sequences. To assess these models, we integrate studies of the architecture and geometry of the El Garia Fm with detailed taphonomic, biometric, biofabric and palaeoecological characterization of *Nummulites* tests. We conclude that the highest rates of sediment production occurred in euphotic water over the palaeohighs and in nearshore environments. *Nummulites* on the palaeohighs were transported into the surrounding deeper water by oceanic and storm currents that swept the platform top, producing a nummulitic sediment package that thickened and became increasingly fine-grained and fragmented into outer ramp environments. This transport exerted a major control on development of the ramp-like geometries often seen at outcrop. Our findings question the validity of a recent sequence stratigraphic model that identifies decimetre-scale Milankovitch cycles, even in largely allochthonous, 'bio-retextured', mid/outer ramp sediments. Our findings also suggest that the thin packages of El Garia Fm on the palaeohighs, which have previously been interpreted as condensed sections that can be correlated with thicker, more distal accumulations, actually represent remnants of the sediment that was produced on the highs and 'exported' into the basin.

Keywords Carbonate platform, El Garia Formation, Eocene, larger benthic foraminifera, *Nummulites*, Tunisia.

INTRODUCTION

During the early Tertiary, following the demise of the end Cretaceous rudist-coral assemblage, nummulitid (*Nummulites*, *Assilina* and *Operculina*), orthophragminid (*Discocyclina*) and alveolinid (*Alveolina*) larger benthic foraminifera (LBF) thrived on shallow, oligotrophic, circum-Tethyan carbonate platforms (Buxton & Pedley, 1989). Amongst the early Cenozoic LBF, *Nummulites* were unique in their rock-forming potential. They are abundant in Palaeocene to Upper Eocene sediments of the Mediterranean and Arabian Peninsula, where nummulitic limestones form hydrocarbon reservoirs in offshore North Africa and India, and are potential exploration targets in the Middle East. *Nummulites* are also known from Indonesia and the Americas, although they are represented by comparatively fewer species in the latter (Adams, 1967).

Despite the importance of this group of LBF as sediment contributors, there are contradictions in the recent literature about the location of the *Nummulites* 'factory' (e.g. Loucks *et al.*, 1998; Sinclair *et al.*, 1998; Allen *et al.*, 2001; Pomar, 2001). Resolving this issue is important for our understanding of the development of early Tertiary carbonate platforms, which are mainly ramps because of the lack of frame-building organisms capable of building steep-margined platforms. To address the issue of the sediment production profile of *Nummulites*, we focused on outcrops of the early Eocene El Garia Formation (Metlaoui Group) in Tunisia (Fig. 1). These sediments are the subject of recently published depositional, sequence-stratigraphic and reservoir models (e.g. Loucks *et al.*, 1998; Jorry *et al.*, 2003; Vennin *et al.*, 2003), which exhibit marked differences in terms of *Nummulites* production and accumulation profiles, and the continuity, correlation and resolution of depositional sequences. To critically assess these models, we integrated large-scale studies of platform location, architecture and geometry of the El Garia Fm with a much finer-scale morphological, taphonomic and biofabric characterization of *Nummulites* tests and populations. We integrate our observations with studies of the ecology of extant nummulitids and other LBF to evaluate the location of the *Nummulites* 'factory' and examine the role of transport (and other extrinsic/intrinsic processes) in controlling the depositional profile and stratigraphic architecture of the El Garia Fm.

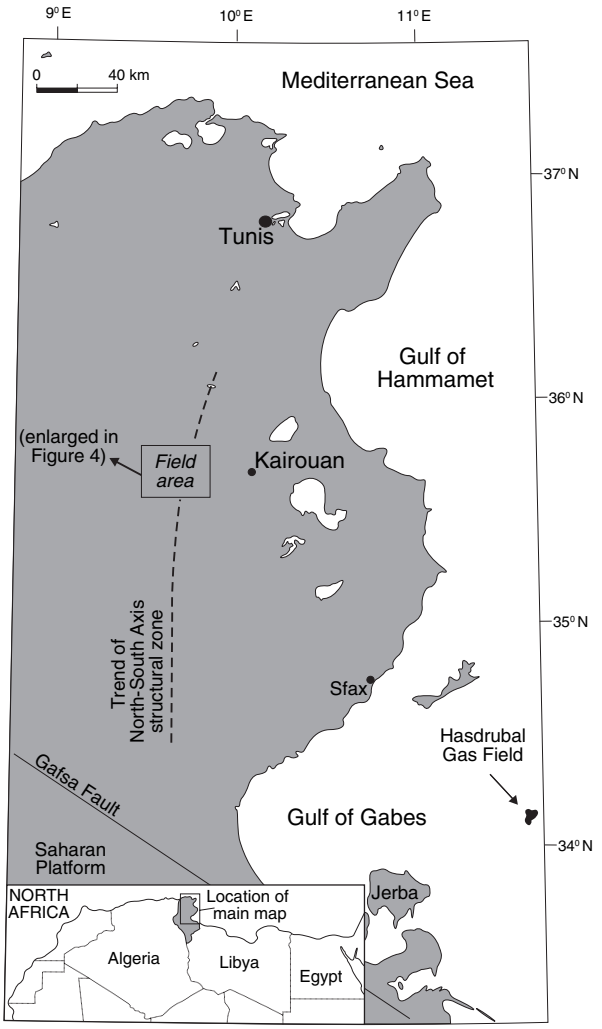


Fig. 1. Map of north and central Tunisia, showing position of the field area. Trend of the 'North–South Axis' structural zone (referred to in text) after Morgan *et al.* (1998).

GEOLOGICAL SETTING

During the early Eocene, what is now Tunisia was located on the southern margin of the Tethys Ocean, at a latitude of *ca* 22°N (Dercourt *et al.*, 2000). Deposition on Eocene peri-cratonic carbonate platforms that developed on this part of the southern Tethyan margin was strongly influenced by salt mobilization and active structures. At the Libyan end of the Gabes-Tripoli Basin, salt diapirism created a steep-margined shelf, whilst deposition along the Tunisian margin occurred on ramps and was influenced by emergent areas such as Kasserine and Jaffara Islands, which had appeared during the late Cretaceous (Fournie, 1975; Bishop, 1988; Moody & Grant, 1989; Philip *et al.*, 1997; Loucks *et al.*, 1998; Zaïer *et al.*, 1998; Anketell & Mriheel, 2000). Sedimentation in basins surrounding these islands was influenced by the North–South Axis (NOSA; see Fig. 1), a structural zone characterized by palaeohighs and grabens, which resulted in a series of small *en echelon* basins (Zaïer *et al.*, 1998). The Palaeocene–Eocene sediments deposited within basins to the north and east of Kasserine Island are largely represented by the El Haria Fm, the Metlaoui Group, the Cherahil Fm and the Souar Fm (Fig. 2).

The Metlaoui Group, of which the El Garia Fm is part, comprises a series of prograding sediments deposited on a NE-facing ramp (Loucks *et al.*, 1998). They are underlain by the phosphate- and glauconite-rich sediments of the transgressive Chouabine Fm, and show facies variations from NE to SW (see Fig. 3) (Bishop, 1988). The nummulitic limestones of the El Garia Fm attain a maximum thickness of 160 m

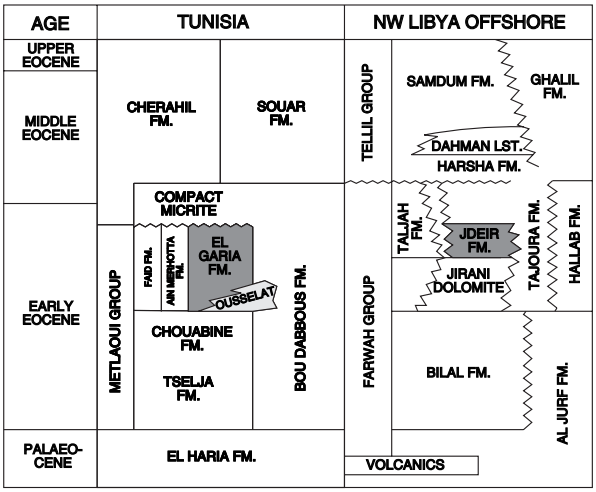


Fig. 2. Regional lithostratigraphic correlation for the late Palaeocene and Eocene of Tunisia and offshore NW Libya. Note highlighted nummulitic El Garia Formation and its lateral equivalent in offshore north-west Libya (modified from Racey, 2001).

at Djebel Cherahil, in north-central Tunisia (Comte & Lehmann, 1974). Together with their lateral equivalent, the Jdeir Fm, they represent prolific *Nummulites* deposition in a broad zone that today extends NW from offshore Libya, through the Gabes-Tripoli Basin, and across central Tunisia to the Algerian border. Seaward, the El Garia Fm passes through the Ousselat Member, a transitional 'fringe' of broken *Nummulites* fragments ('nummulithoclastic' debris), into the deep-water globigerinid limestones of the Bou Dabbous Fm, which was the source rock for the hydrocarbons that accumulated in El Garia Fm reservoirs (Bishop, 1988; Bailey *et al.*, 1989; Moody & Grant, 1989; Racey *et al.*, 2001). Time-equivalent continental facies with evaporites (Faid Fm) and gastropodal/algal dolomites and evaporites (Ain Merhotta Fm) were deposited to the south of the nummulitic El Garia Fm, close to the emergent areas. The El Garia Fm is

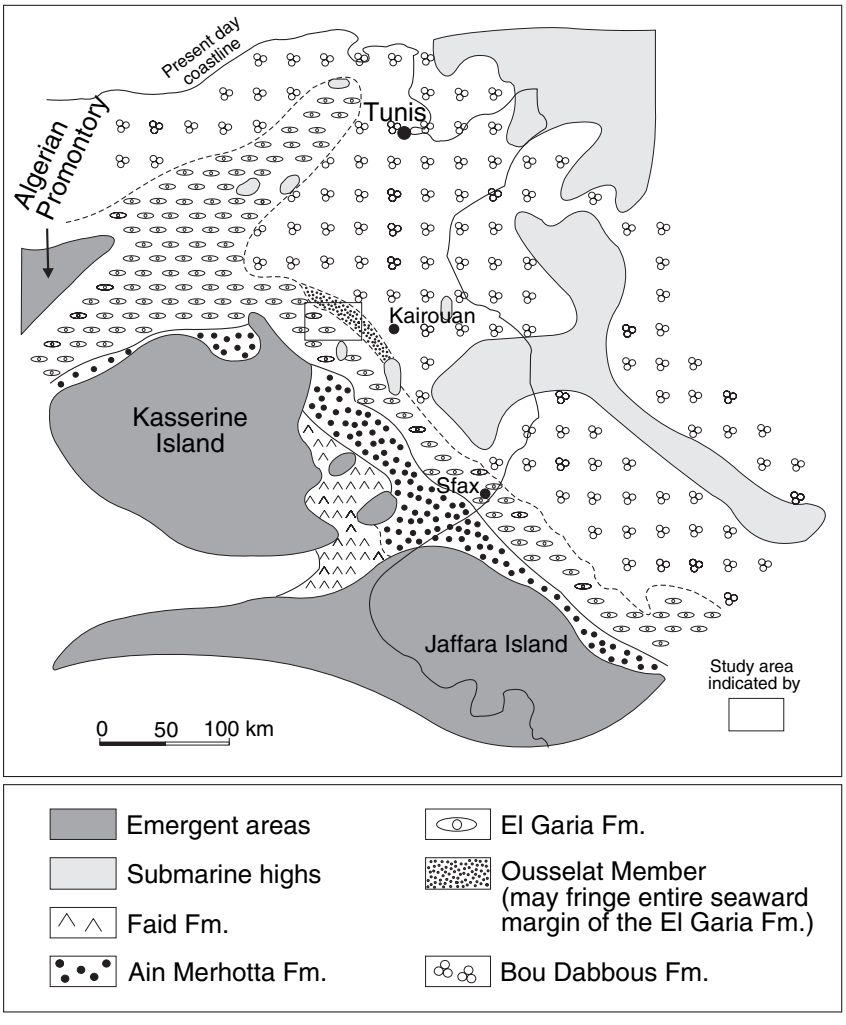


Fig. 3. Early Eocene palaeogeography and Metlaoui Group facies distribution for north-central Tunisia and the Gulf of Gabes (note modern coastline overlay) (modified from Bishop, 1988; Moody & Grant, 1989; Zaïer *et al.*, 1998).

capped by an argillaceous carbonate unit referred to as the Compact Micrite Member of the Cherahil Fm. In more distal settings, the Cherahil Fm is replaced by the deep-water Souar Fm. Significant palaeotopographic relief during deposition of the El Garia Fm is indicated by the variation in the age of units underlying the El Garia Fm, including the Palaeocene El Haria Fm and various Cretaceous units, and by thinning of the El Garia and underlying units over palaeohighs (Racey *et al.*, 2001).

PREVIOUS WORK ON THE EL GARIA FORMATION

The El Garia Fm has been the subject of a series of studies, reflecting the economical hydrocarbon reserves within the El Garia Fm in the Gulf of Gabes, and its lateral equivalent, the Jdeir Fm, offshore north-west Libya. These studies have identified the broad Metlaoui Group facies pattern, the role of topographic and structural highs during deposition, and also the diagenetic sequence and reservoir characteristics (e.g. Fournie, 1975; Bishop, 1985, 1988; Bernasconi *et al.*, 1987; Moody, 1987; Bailey *et al.*, 1989; Moody & Grant, 1989; Loucks *et al.*, 1998; Anketell & Mriheel, 2000; Macauley *et al.*, 2001; Racey *et al.*, 2001; Jorry *et al.*, 2003; Vennin *et al.*, 2003). Therefore, with the broad palaeogeographic, stratigraphic and structural context already described, and with good outcrop and subsurface data available, the El Garia Fm provides the opportunity to address the role of *Nummulites* within early Tertiary carbonate deposystems.

METHODOLOGY

From outcrops of the El Garia Fm to the west of Kairouan, four main locations were studied, collectively allowing assessment of the characteristics of the El Garia Fm from the inner to outer ramp, as detailed in Fig. 4. Where possible, beds were 'walked out' in the field to determine lateral variability away from logged positions and to aid the assessment of the dimensions of *Nummulites* accumulations.

The El Garia Fm is predominantly composed of intact and fragmented *Nummulites*, which results in a lack of clearly defined sub-facies divisions. Hence, traditional approaches to lithofacies differentiation are impractical. Instead, sub-division of the El Garia Fm has largely been based on a bio-/tapho-facies approach, incorporating: (i) visual estimates (using published charts) of all grains and matrix in acetate peels and thin sections; (ii) assessment of the autochthonous/allochthonous nature of the nummulitid tests, based upon taphonomic analysis and comparison with the criteria defined by Beavington-Penney (2004) for the recognition of *in situ* and transported *Nummulites* in thin section; (iii) counts of the number of intact (and therefore *in situ*?) *Nummulites* present (and their density per cm^2); (iv) test size and shape; (v) the ratio of megalospheric (A-form) to microspheric (B-form) *Nummulites*; and (vi) the texture and 'biofabric' of the rock. Fragmented/abraded (i.e. allochthonous) *Nummulites* have been 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).

Morphological characteristics of *Nummulites* tests, e.g. diameter/thickness (*D*/*T*) ratio, have also been used to refine facies sub-divisions and/or interpret depositional environments of facies inferred to represent palaeocommunities (i.e. autochthonous or parautochthonous assemblages). Studies of living nummulitids and other symbiont-bearing LBF have clearly shown that there is a trend of test-shape change with water depth (reviewed in Beavington-Penney & Racey, 2004). Within taxa, tests from deep photic zone environments are much flatter than those from shallow, brightly lit water. We used relative differences in *D*/*T* measurements of *Nummulites* from the El Garia Fm to assist palaeobathymetric comparison between facies. Such analysis is based only on data from A-form *Nummulites*, as the B-form data set is significantly smaller, mainly because of the large test size of B-forms 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 only be made where a true axial section of the test is exposed. As 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, analysis of *Nummulites* biometric data (especially *D*/*T* ratio groupings on histograms), backed up by visual analysis of thin sections and acetate peels (Beavington-Penney, 2002), indicates that El Garia facies are overwhelmingly dominated by one or two similarly shaped species.

Numerous authors have applied observations on the ecology of living LBF to older Cenozoic

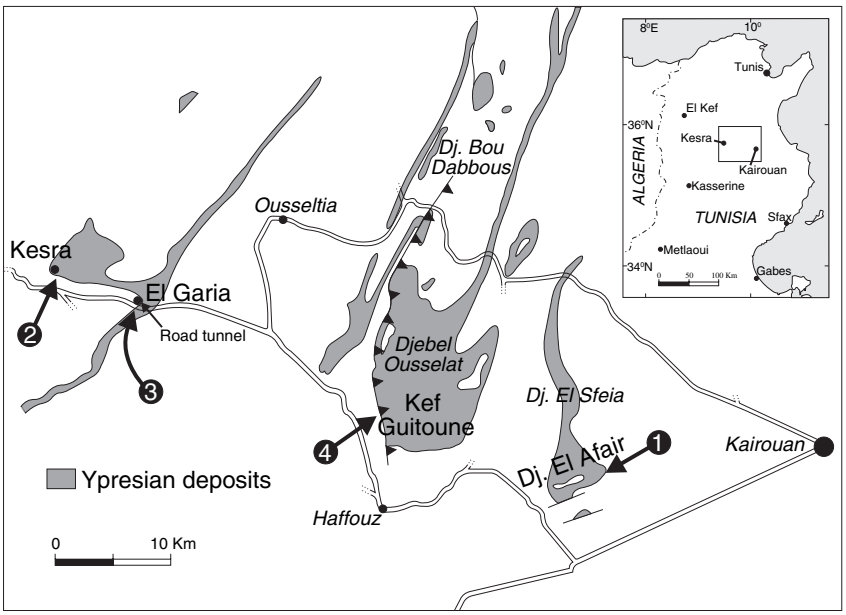


Fig. 4. Map of the area to the west of Kairouan, showing Ypresian outcrops and location of studied sections (arrowed/numbered). Thrust to west of Djebel Ousselat has displaced Ypresian deposits over Eocene sediments (modified from Rigane *et al.*, 1994). Field guides to the area by ben Jemia-Fakhfakh (1997) and Grocott *et al.* (1998) were used to identify the four main study locations: (1) Djebel el Afair (inner ramp); (2) Kesra (palaeohigh in mid-ramp setting); (3) El Garia village (mid ramp); and (4) Kef Guitoune (mid/outer ramp).

assemblages. However, palaeo-water-depth estimations based on Eocene foraminifera provide only relative depth data, since there is evidence that throughout the Cenozoic, nummulitids (and other LBF) were forced to occupy deeper water habitats through time, due to the colonization of the shallowest water environments by 'novel' genera (Chaproniere, 1975; Buxton & Pedley, 1989; Hohenegger, 1999). Therefore, palaeobathymetric interpretations in this study are limited to broad, qualitative sub-divisions, and use the following scale: 'very shallow' (above fair weather wave base); 'shallow' (between fair weather wave base and storm wave base); 'deep' (below storm wave base but still within the photic zone); and 'very deep' (below the photic zone).

'Biofabric' interpretations, based on both field observations and a thin-section/acetate peel study, utilized published work on the fabric of *Nummulites* accumulations (e.g. Aigner, 1985; Racey, 1995). Also used were sediments containing comparable bioclasts, such as centimetre-scale *Halimeda* grains within the bioturbated mud mounds of Florida Bay (e.g. Tudhope & Scoffin, 1984; Tedesco & Wanless, 1991, 1995). The key biofabric types and their interpretations are summarized in Fig. 5.

FACIES DESCRIPTIONS, ASSOCIATIONS AND INTERPRETATION

Macro- and micro-facies descriptions and biometric data are presented in Table 1. Micro-facies are illustrated in Fig. 6, whilst macro-facies characteristics are illustrated later within facies-association interpretations. Textural classification follows Dunham (1962) and Mount (1985). Facies associations are illustrated in Fig. 7. Individual facies identified in this study are usually restricted to one of the four key geographical areas identified in Fig. 4; few facies occur in more than one area. Hence, it has not been possible to define traditional genetic facies associations. Rather, associations of facies are interpreted within their (often sedimentologically discrete) geographical areas. Relationships between facies in each of these four areas are described below.

Djebel Afair facies association

Djebel Afair is located at the eastern edge of the study area (see Fig. 7). A *ca* 40 m thick package of the El Garia Fm crops out, although neither the upper nor lower contacts are exposed. Landward, this unit passes into the restricted, shallow lagoonal deposits of the Ain Merhotta Fm and the sabkhas of the Faid Fm (Moody, 1987; Loucks *et al.*, 1998; see Fig. 3). Basinwards, the unit grades into mid-ramp to outer ramp El Garia Fm (Grocott *et al.*, 1998). As noted in Table 1, and illustrated in Fig. 8, outcrops at this locality are dominated by the cross-bedded, quartzose, LBF/red algal, sheet-like grainstones of Facies DA. These sediments pass upwards conformably into the A-form-dominated nummulitic grainstones of Facies NA-1, which in turn pass conformably into an inter-bedded association of NB-1 and NC2-2.

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?	

Biofabric	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	
		Tubular tempestite figures modified from Tedesco & Wanless (1991)

Fig. 5. Key *Nummulites* biofabric types, summarized from published work on the fabric of nummulitic limestones, and sediments containing comparable grains (e.g. centimetre-scale *Halimeda* grains within the bioturbated and storm-swept mud mounds of Florida Bay).

Table 1. Macro- and micro-facies descriptions and biometric data.

Facies characteristics	*Nummulites* biometrics
Sub-facies DA-1. Sandy, larger foraminiferal-red algal limestone (see Fig. 6A)	
Macro: metre-scale beds, 1–2·5 m thick, and laterally extensive for hundreds, occasionally thousands of metres. Unidirectional, tabular cross-bedding is common, with (weathered) high angle foresets (av. 22°) and metre-scale sets (suggesting N to NE palaeocurrent directions). Biofabrics: 'isolated imbrication' and 'chaotic stacking'; clusters of imbricated LBF tests commonly with bipolar dip directions, aligned with the often poorly defined foresets	No intact *Nummulites* present
Micro: quartz (angular to sub-r, coarse-grained, moderately to poorly sorted) (30%); *Nummulites* fragments (2·3%); ovate *Discocyclina* (2%); coralline red algae (as abraded fragments of articulated forms and possible crustose forms) (4%); echinoid fragments (3%); minor components: fine n'clastic debris	
Sub-facies DA-2. Quartzose, larger foraminiferal-red algal grainstone (see Fig. 6B)	
Macro: sheet-like beds, 0·5–2·5 m thick, and hundreds to thousands of metres in extent. Bedforms and biofabrics as for DA-1, although rare bioturbation fabrics are evident. The youngest bedding plane of this facies is encrusted by *in situ* bivalves (including oysters)	A : B ratio: commonly only A-forms are present; where B-forms occur ratio varies from 32 : 1 to 41 : 1 Density: A-form av. = 1·9/cm^{-2}; B-form av. = 0·2/cm^{-2}
Micro: quartz (as for Sub-facies DA-1) (average 6·6%); *Nummulites* fragments (9%); ?*in situ Nummulites* (3·8%); n'clastic debris (3%); ovate *Discocyclina* (elongate forms also present) (5·8%); coralline red algae (as for Sub-facies DA-1) (2·4%); echinoid fragments (5·8%); SBF (2%); minor components: glauconite, ostracods, miliolids, bryozoan fragments, serpulid tubes, phosphate grains and ?brachiopod spines	Test size/shape (data in mm): A-form D/T av. = 2·44; SD = 0·61; n = 63, A-form D av. = 1·89; SD = 0·62; n = 65
Facies DA sub-divided on the basis of: cross-bedding in DA-1; abundance of quartz; and bioturbation in DA-2	
Sub-facies NA-1. Quartzose nummulitic grainstone (A-form dominated) (see Fig. 6C)	
Macro: metre-scale, sheet-like beds, up to 3·2 m thick, and laterally extensive for hundreds to thousands of metres. Rare, poorly defined tabular cross-bedding was identified at Djebel Afair. Biofabrics: 'chaotic stacking', 'contact imbrication'; rare 'sub-horizontal stacking' and 'linear accumulation' biofabrics were also observed	A : B ratio: locally only A-forms are present, but where B-forms occur ratio varies from 22 : 1 to 157 : 1 Density: A-form av. = 19/cm^{-2}; B-form av. = 0·3/cm^{-2}
Micro: *in situ Nummulites* (30·9%); quartz (sub-a to sub-r, fine- to very coarse-grained) (2·8%); *Discocyclina*; elongate and ovate forms present (2·6%); *Nummulites* fragments (3·1%); n'clastic debris (10%); echinoid fragments (2·3%); minor components: SBF, ostracods, glauconite, coralline red algae, serpulid tubes, micrite, and rare ?planktonic foraminifera	Test size/shape (data in mm): A-form D/T av = 2·63; SD = 0·99; n = 118, A-form D av. = 2·20; SD = 0·81; n = 121
Sub-facies NA-2. Nummulitic grainstone (A-form dominated) (see Fig. 6D)	
Macro: as for NA-1, although this sub-facies lacks the cross-bedding seen in NA-1 at Djebel Afair	A : B ratio: varies from 57 : 1 to 144 : 1
Micro: *in situ Nummulites* (62·5%); *Nummulites* fragments (6·5%); n'clastic debris (1·5%); elongate *Discocyclina* (intact and broken forms) (2·5%); minor components: fine n'clastic debris, echinoid fragments, SBF, fine-grained, sub-a to sub-r quartz and patches of micrite	Density: A-form av. = 10·3/cm^{-2}; B-form av. = 0·2/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 2·84; SD = 0·50; n = 27, A-form D av. = 2·29; SD = 0·53; n = 27
Sub-facies NA-3. Nummulitic grainstone (A-form dominated; B-form 'enriched')	
Macro: as for NA-1, although this sub-facies lacks the cross-bedding seen in NA-1 at Djebel Afair	A : B ratio: varies between 6 : 1 and 9 : 1
Micro: *in situ Nummulites* (53·3%); *Nummulites* fragments (10%); n'clastic debris (8·3%); fine n'clastic debris (9%); echinoid fragments (4·3%); elongate *Discocyclina* (5%); minor components: quartz (sub-a to sub-r, fine- to coarse-grained), SBF and patches of micrite	Density: A-form av. = 3·9/cm^{-2}; B-form av. = 0·5/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 2·64; SD = 0·43; n = 16, A-form D av. = 2·64; SD = 0·65; n = 20
Facies NA sub-divided on the basis of: cross-bedding within NA-1; presence of quartz and *Discocyclina* in NA-1; ratio of A- to B-form *Nummulites*; and differences in associated facies	

Table 1. Continued.

Facies characteristics	*Nummulites* biometrics
Sub-facies NB-1. Quartzose nummulitic packstone (B-form dominated)	
Macro: massively bedded, with beds varying between 0·75 and 4·0 m thick. Biofabrics: 'sub-horizontal stacking', 'contact imbrication' and 'chaotic stacking' *Micro*: *in situ Nummulites* (48·5%); n'clastic debris (9·5%); micrite (6%); echinoids (4%); quartz (angular to sub-rounded, medium- to very coarse-grained) (2·5%); minor components: elongate *Discocyclina*, SBF, serpulid tubes, gastropods, ?bryozoan fragments, rare ?planktonic foraminifera and ?halimedacean green algae	A : B ratio: average ratio of 1 : 4 Density: A-form av. = 2·6/cm^{-2}; B-form av. = 0·7/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 3·34; SD = 0·11; n = 5, A-form D av. = 3·43; SD = 0·05, n = 5
Sub-facies NB-2. Nummulitic packstone (B-form dominated/'enriched') (see Fig. 6E)	
Macro: as for NB-1, although rare 'linear accumulation' biofabrics were observed in this sub-facies *Micro*: *in situ Nummulites* (38·2%); n'clastic debris (12·4%); *Nummulites* fragments (12·8%); fine n'clastic debris (7·6%); echinoid fragments (3·8%); micrite (13%); minor components: bivalve (?oyster) fragments, ?crustacean fragments, SBF and rare fine-grained quartz *Facies NB sub-divided on basis of:* presence of quartz in NB-1; differences in associated facies	A : B ratio: 1 : 1 to 1 : 2 Density: A-form av. = 1·2/cm^{-2}; B-form av. = 1·8/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 3·33; SD = 1·49; n = 11, A-form D av. = 3·18; SD = 0·68; n = 14
Sub-facies NC1-1. Fine nummulithoclastic debris wackestone (locally packstone)	
Macro: forms extensive beds, 1–4 m thick, several kilometres in extent, and bounded by prominent bedding planes. Biofabrics: 'sub-horizontal stacking', 'isolated chaotic' and 'tangential circular' *Micro*: fine n'clastic debris (38·8%); n'clastic debris (8·8%); *Nummulites* fragments (4·3%); *in situ Nummulites* (3%); micrite (30%); SBF (including *Cibicidoides* sp., *Bulimina* sp., *Stainforthia* spp., *S. kamali*, *Nodosaria* sp., *Polymorphina* sp. and *Baggina* sp.) (3·8%); echinoid fragments (4·1%); minor components: elongate *Discocyclina*, ostracods, quartz, ?crustacean fragments, planktonic foraminifera, rare ?*Operculina* and phosphate	A : B ratio: commonly only A-forms present; where B-forms occur ratio varies from 2 : 1–23 : 1 Density: A-form av. = 1·0/cm^{2}; B-form av. = 0·03/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 6·87; SD = 1·59; n = 15, A-form D av. = 3·42; SD = 1·10; n = 22
Sub-facies NC1-2. Nummulitic-fine nummulithoclastic debris wackestone (locally packstone) (see Fig. 6F)	
Macro: as for NC1-1 *Micro*: fine n'clastic debris (26%); *in situ Nummulites* (14·4%); *Nummulites* fragments (8·7%); n'clastic debris (11%); micrite (21·9%); echinoid fragments (4·6%); SBF (2·9%); minor components: elongate *Discocyclina*, articulated ostracods, quartz (angular to sub-r, fine-grained), rare planktonic foraminifera and phosphate *Facies NC1 sub-divided on basis of:* the presence of elongate A-form Nummulites in NC1-2	A : B ratio: commonly only A-forms are present; where B-forms occur ratio varies from 2 : 1 to 52 : 1 Density: A-form av. = 3·4/cm^{-2}; B-form av. = 0·4/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 7·42; SD = 2·88; n = 16, A-form D av. = 3·23; SD = 0·86; n = 18
Sub-facies NC2-1. Nummulithoclastic debris packstone (locally grainstone)	
Macro: bedforms as for Facies NC1. Poorly defined current ripples also identified. Biofabrics: 'contact imbrication', 'sub-horizontal stacking', 'chaotic stacking' and 'tangential circular'; *Thalassinoides* locally present *Micro*: n'clastic debris (28·3%); *Nummulites* fragments (14·2%); fine n'clastic debris (15·5%); *in situ Nummulites* (8·6%); micrite (13%); echinoid fragments (5·6%); elongate *Discocyclina* (2·8%); SBF (1·1%); minor components: ostracods, quartz, ?crustacean fragments (including ?crabs), bivalve fragments, rare phosphate, glauconite and ?planktonic foraminifera	No intact *Nummulites* present

Table 1. Continued.

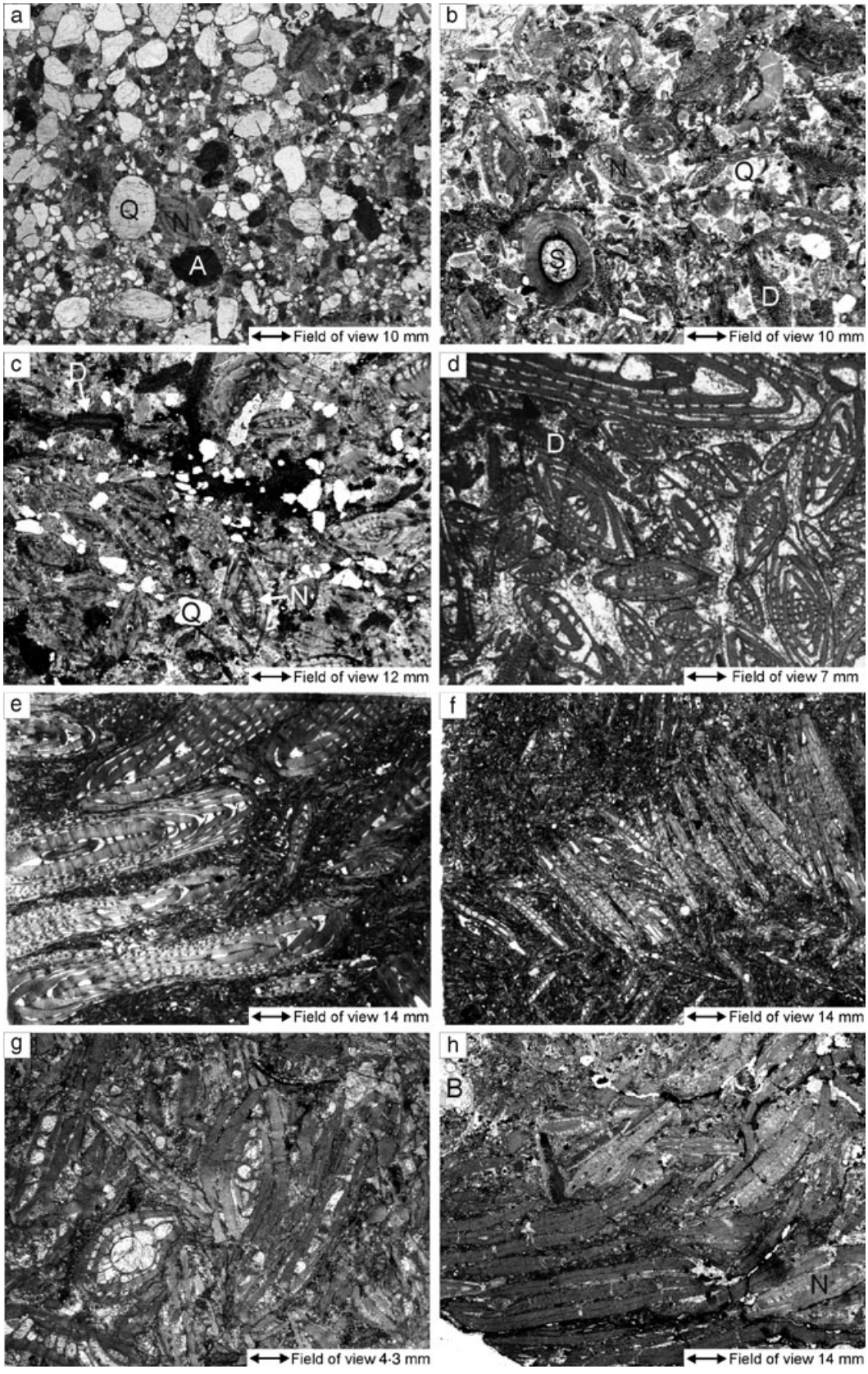
Facies characteristics	*Nummulites* biometrics
Sub-facies NC2-2. Nummulithoclastic debris packstone *Macro*: as for NC2-1, although lacks the possible current ripples and distinct *Thalassinoides* bioturbation *Micro*: micrite, often as (?faecal) pellets (17%); *in situ Nummulites* (6·5%); *Nummulites* fragments (15%); n'clastic debris (25%); fine n'clastic debris (9%); echinoid fragments (6%); quartz (sub-r to sub-a, medium- to very coarse-grained) (1·5%); ?corals (with possible macro-borings); ?bivalves (with possible micrite envelopes); minor components: ovate *Discocyclina*, SBF, ?brachiopod fragments, planktonic foraminifera and sharks' teeth *Facies NC2 sub-divided on basis of*: possible current ripples in NC2-1; bioturbation within NC2-1; presence of quartz in NC2-2; large bioclasts (including probable corals and bivalves) in NC2-2; and associated facies	No intact *Nummulites* present
Sub-facies NC3. Fragmented *Nummulites* grainstone (locally packstone) (see Fig. 6G) *Macro*: forms dm–m-scale, massive beds (up to 3·5 m thick); at El Garia village and Kef Guitoune beds are laterally extensive for up to several km; at Kesra they are laterally persistent for several hundreds of metres. Scoured surfaces and rare, poorly defined tabular and ?trough cross-bedding were identified at Kesra. Palaeocurrent directions obtained from the latter suggest transport to the NW. Biofabrics: 'isolated imbrication', 'chaotic stacking', 'tangential circular', 'stacked deflected' and 'sub-horizontal stacking'; 'linear accumulations' were observed at Kesra, and *Thalassinoides* burrows were identified in all areas *Micro*: *Nummulites* fragments (36·6%); *in situ Nummulites* (10·4%); n'clastic debris (16·6%); fine n'clastic debris (7·1%); echinoids (4·1%); elongate *Discocyclina* (2·9%); minor components: SBF, ostracods, serpulid tubes, quartz, micrite, glauconite, phosphate, bivalve (including oyster) fragments, and rare gastropods	No intact *Nummulites* present
Sub-facies DC-1. Elongate *Discocyclina* wackestone (locally packstone) *Macro*: massively bedded on a dcm-, rarely m-scale. Biofabrics: 'isolated chaotic' and 'tangential circular' (the latter occasionally within well-defined *Thalassinoides* burrows) *Micro*: elongate *Discocyclina* tests (commonly broken, although intact forms observed within *Thalassinoides* burrows) (20·7%); *in situ Nummulites* (16·7%); *Nummulites* fragments (8·7%); n'clastic debris (1·7%); micrite (often as ?faecal pellets, and also partially infilling LBF chambers) (21·3%); SBF (5·3%); echinoid fragments (2·3%); phosphate (3%); glauconite (commonly within SBF tests) (3·7%); quartz (sub-a, medium-grained, locally granule-sized) (1·3%); minor components: serpulid worm tubes, bivalve fragments and fine n'clastic debris	A : B ratio: A-forms dominate, and are often the only type present; where B-forms occur the ratio varies from 21 : 1 to 52 : 1 Density: A-form av. = 2·2/cm^{-2}; B-form av. = 0·03/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 4·05; SD = 0·71; n = 27, A-form D av. = 3·27; SD = 0·63; n = 27
Sub-facies DC-2. Elongate *Discocyclina* packstone (see Fig. 6H) *Macro*: bedded on a metre scale. Tabular cross-bedding suggests transport to the NW to NE. Biofabrics: 'chaotic stacking', 'contact imbrication', 'sub-horizontal stacking', 'linear accumulations' (<1·8 m wide) on scoured surfaces *Micro:* elongate *Discocyclina* (15·7%); *in situ Nummulites* (25·3%); *Nummulites* fragments (12·1%); n'clastic debris (5·9%); echinoid fragments (4·5%); micrite (locally reaches 18%); SBF (1·5%); serpulid tubes (1·3%); minor components: ostracods, quartz, phosphate, glauconite, ?bivalves, fine n'clastic debris and oyster fragments	A:B ratio: A-forms often the only type present; where B-forms occur ratio varies from 6:1 to 82:1 Density: A-form av. = 4·0/cm^{-2}; B-form av. = 0·2/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 4·26; SD = 0·95; n = 67, A-form D av. = 3·42; SD = 0·81; n = 67

Table 1. Continued.

Facies characteristics	*Nummulites* biometrics
Sub-facies DC-3. Elongate *Discocyclina* wackestone (locally packstone) *Macro*: as for DC-1 *Micro*: elongate *Discocyclina* (7%); n'clastic debris (16·5%); *Nummulites* fragments (6%); fine n'clastic debris (7·5%); micrite (35%); SBF (8·5%); quartz (5%); phosphate (4%); glauconite (3·5%); minor components: *in situ Nummulites*, ?bryozoans, serpulid tubes, echinoids and ?dasycladacean algae *Facies DC sub-divided on basis of*: texture; cross-bedding within DC-2; taphonomy of *Discocyclina* tests; paucity of *in situ Nummulites* in DC-3; accumulations of *Nummulites* on ?scoured surfaces in DC-2; and associated facies	A:B ratio: Commonly no A or B-forms are present; where present A-forms dominate (ratio up to 14:1) Density: A-form av. = 1·1/cm^{-2}; B-form av. = 0·1/cm^{-2} Test size/shape (data in mm): A-form D/T av. = 3·99; SD = 1·68; n = 5, A-form D av. = 3·28; SD = 0·86; n = 5
Sub-facies CH-1. Nodular SBF wackestone *Macro*: indistinctly bedded on a dcm-, occasionally m-scale *Micro*: micrite (48%); SBF (including *Stainforthia* sp., *S. troosteri*, *Nodosaria* sp. and *Bulimina* sp.) (13%); gastropods and ?bivalves, replaced by non-ferroan calcite spar (14%); thin-walled bivalves (4%); ostracods (3%); serpulid tubes (2%); minor components: quartz, glauconite, phosphate, echinoids and fine ?n'clastic debris	No intact *Nummulites* present
Sub-facies CH-2. SBF-nummulithoclastic wackestone (locally packstone) *Macro*: as for CH-1, although lacks the nodular bedding seen in both CH-1 and CH-3 *Micro*: micrite (51%); SBF (including *Stainforthia globigerina*, *S. stahensis*, *S. troosteri*, *Cibicidoides* sp., *Lenticulina* sp. and ?*Elphidiella* cf. *elevatus*) (9%); bivalves (6·3%); gastropods (5%); unidentified bioclasts replaced by non-ferroan calcite spar (8%); fine n'clastic debris (5·3%); *Nummulites* fragments (1·7%); n'clastic debris (2%); phosphate (4%); glauconite (1·7%); serpulid tubes (1·7%); ostracods (2%); minor components: quartz, miliolids and echinoid fragments	No intact *Nummulites* present
Sub-facies CH-3. Nodular SBF wackestone *Macro*: as for CH-1 *Micro*: micrite (60%); SBF (*Stainforthia* sp. and *Bulimina* sp.) (20%); miliolids (3%); ostracods (3%); echinoids (2%); phosphate (1·5%); minor components include: quartz, ?bryozoans, glauconite, and fine ?n'clastic debris *Facies CH sub-divided on basis of:* bioclasts replaced by sparry calcite in CH-1 and -2; nodular appearance of CH-1 and -3; abundance of n'clastic debris in CH-2; palaeobathymetric interpretation of SBF; and associated facies	No intact *Nummulites* present

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.
Abbreviations: n'clastic, nummulithoclastic; SBF, smaller benthic foraminifera; sub-a, sub-angular; sub-r, sub-rounded; abbreviations in 'Biometrics' column: D, diameter; T, thickness; av., average; SD, standard deviation; *n*, number of tests measured.

Fig. 6. Photomicrograph captions. (a) Sub-facies DA-1. Sandy, larger foraminiferal-red algal limestone. Note abundant quartz (Q), plus *Nummulites* fragments (N) and abraded fragments of coralline red algae (A). (b) Sub-facies DA-2. Quartzose, larger foraminiferal-red algal grainstone. Note common ovate *Discocyclina* (D), A-form *Nummulites* (which are often abraded) (N), quartz (Q) and serpulid tube (S). (c) Sub-facies NA-1. Quartzose nummulitic grainstone (A-form dominated). Note abundant intact A-form *Nummulites* (N), quartz (Q) and elongate *Discocyclina* (D). (d)Sub-facies NA-2. Nummulitic grainstone (A-form dominated). Note elongate *Discocyclina* (D) and rare B-form *Nummulites* (top of the photomicrograph). (e) Sub-facies NB-2. Nummulitic packstone (B-form dominated). (f) Sub-facies NC1–2. Nummulitic-fine nummulithoclastic debris wackestone (locally packstone). Note elongate *Nummulites* exhibiting 'sub-horizontal stacking' biofabric. (g) Facies NC3. Fragmented *Nummulites* grainstone (locally packstone). (h) Sub-facies DC-2. Elongate *Discocyclina* packstone. Note A-form *Nummulites* (N), plus articulated ?bivalve, infilled by coarse, non-ferroan calcite spar (B).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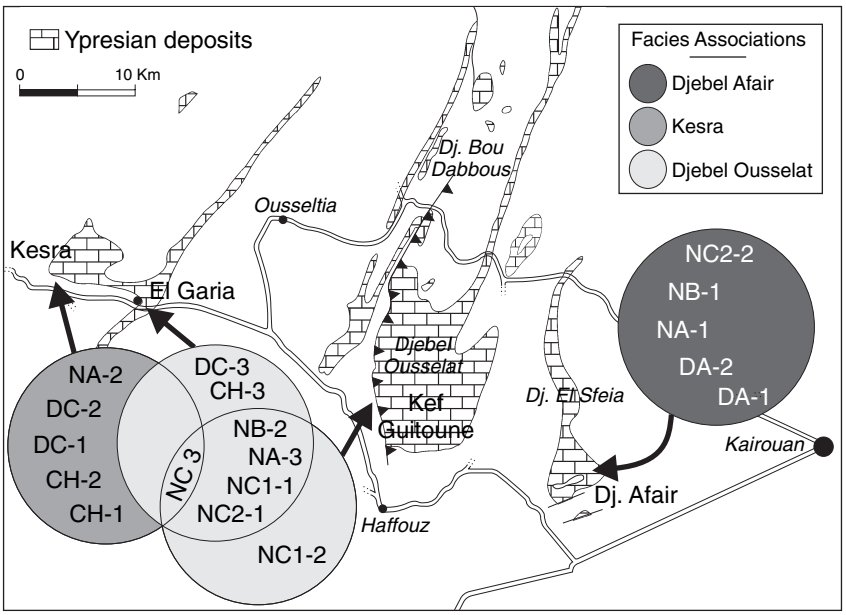

Fig. 7. Facies within the three geographically defined facies associations. A Venn diagram has been used to illustrate facies that are not restricted to one area.

Interpretation of Facies DA (Sub-facies DA-1 and DA-2)

Features similar to the large-scale, largely unidirectional cross-bedding present in this facies have commonly been described in nummulitic limestones (e.g. Erlich *et al.*, 1993; Loucks *et al.*, 1998; Sinclair *et al.*, 1998), and are often assumed to form in very shallow marine environments – the product of tide or combined tide and wave processes. Although tidal cross-bedding has also been documented in water as deep as 100 m (e.g. Tsuji, 1993; Anastas *et al.*, 1997, 1998), a very shallow-water setting during deposition of Facies DA is indicated by the occurrence of abundant abraded fragments of articulated coralline red algae (CRA), as articulated CRA generally occur from the intertidal zone to *ca* 20 m, although they reach their maximum abundance in water <10 m deep (Wray, 1977). Deposition in very shallow water is also indicated by 'isolated imbrication' and 'chaotic stacking' biofabrics, which suggest the influence of current and wave action, respectively (see Fig. 5). Palaeocurrents obtained from the unidirectional cross-bedding (see Table 1) are directed basinward, suggesting the influence of strong ebb-tides. A nearshore environment is indicated by the presence of abundant coarse-grained, moderately to poorly sorted, angular to sub-rounded quartz, suggesting minimal transport distances from source. This siliciclastic material was probably sourced from Kairouan Island, a palaeohigh located several kilometres to the south of Djebel Afair, and comprised, in part, of late Jurassic/early Cretaceous sandstones (ben Jemia-Fakhfakh, 1991; Grocott *et al.*, 1998).

Deposition within a high-energy, inner-ramp setting is further supported by analysis of larger foraminiferal assemblages, which includes 'robust' A-form *Nummulites* in Sub-facies DA-2 (average D/T ratio 2·44; for full biometric data, including numbers of data points and standard deviations see Table 1). Studies of living LBF have indicated that such 'robust', ovate tests are produced by foraminifera that live in 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 & Erez, 1984; Hallock & Glenn, 1986). The presence of ovate *Discocyclina* also suggests deposition in very shallow water, as these LBF almost certainly hosted symbiotic algae (Ferràndez-Cañadell & Serra-Kiel, 1992). These foraminifera are present in small quantities in Sub-facies DA-1, generally as abraded fragments, although the percentage of intact tests increases in Sub-facies DA-2. Whilst all of the LBF material within Sub-facies DA-1 is allochthonous, a taphonomic assessment/interpretation of *Nummulites* test damage suggests that Sub-facies DA-2 contains both allochthonous and parautochthonous tests, as the minimal test damage exhibited by some tests suggests negligible transport distances. Allochthonous *Discocyclina* tests may have originated from the adjacent lagoons of the Ain Merhotta Fm. The mode of life of *Discocyclina* is relatively ambiguous, although Ferràndez-Cañadell & Serra-Kiel (1992) suggested that they

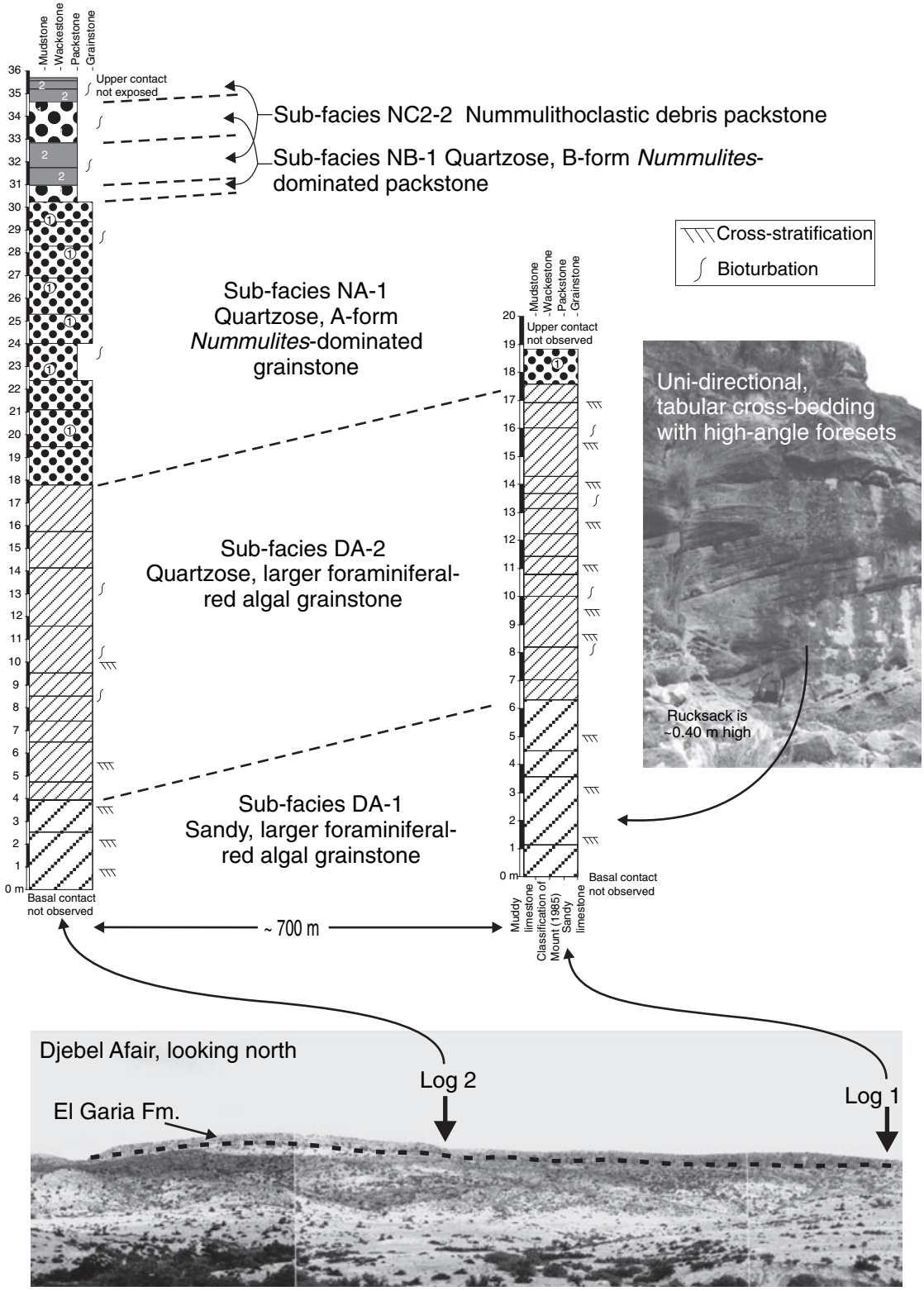

Fig. 8. Djebel Afair facies association.

may have lived on sea-grasses, which Loucks *et al.* (1998) suggested were present in these lagoons.

Interpretation of Sub-facies NA-1

The quartzose, bioclastic grainstones of Sub-facies NA-1 are predominantly a dense assemblage

(average of 19 individuals per square centimetre) of autochthonous and/or parautochthonous A-form *Nummulites*. Deposition in a very shallow marine, nearshore environment is suggested by the presence of sub-angular to sub-rounded, fine to very coarse-grained quartz, and common wave- and current-produced biofabrics. The presence of (rare) patches of micrite also suggests winnowing of the sandbody.

Deposition in very shallow, turbulent water is also indicated by the 'robust' tests of *Nummulites* (average A-form *D*/I 2·6) and *Discocyclina*, as explained within the interpretation of Facies DA. Elongate *Discocyclina* within this facies are likely to be allochthonous, as larger living foraminifera with similarly flattened tests (e.g. *Cycloclypeus carpenteri*) are very easily entrained, and the distributions of living and dead tests are often spatially separate (Hohenegger & Yordanova, 2001).

Studies of modern LBF indicate that A-forms typically dominate the shallowest and deepest parts of a specific depth range (e.g. Leutenegger, 1977; Hottinger, 1982, 1997). Evidence (presented above) of deposition in very shallow water may therefore be reinforced by the dominance of A-forms in this facies. 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 increases in food supply, or rapid population increase in marginal habitats, after mortality events or during colonization of new areas (Lipps, 1982; Harney *et al.*, 1998). They can also occur even where there is an alternation of sexual and asexual generations, because of different survival rates between asexually produced gamonts and initially smaller, sexually produced agamonts. Although the presence of abundant siliciclastic material within this (and adjacent) facies, and the close proximity of the emergent Kairouan Island suggests that terrestrial run-off could have resulted in episodic increases in nutrient flux into nearshore waters, it is not possible to confidently identify the palaeoenvironmental significance of the dominance of A-form *Nummulites* within Sub-facies NA-1, because of the alternative possible interpretations detailed above.

Interpretation of Sub-facies NB-1

The quartzose nummulitic packstones of Sub-facies NB-1 are B-form dominated, with a ratio of *in situ* A- to B-forms of 1 : 4. Increased carbonate mud content (compared with the underlying Facies NA-1), with no evidence of a restricted fauna, indicate deposition in deeper, less turbulent water than that suggested for NA-1. This interpretation is reinforced by the presence of (admittedly rare) planktonic foraminifera. Biofabrics also suggest a decrease in water energy levels. 'Contact imbrication' biofabrics suggest that energy levels were periodically high enough to rework and winnow the accumulation (Laming, 1966; Futterer, 1982), although the presence of *in situ* burrowing echinoids and common 'sub-horizontal stacking' biofabrics suggest that 'chaotic stacking' fabrics are more likely to have been caused by bioturbation (Goldring, 1991) than constant wave agitation (see Fig. 5).

Test morphology of larger foraminifera also suggests deposition in deeper water than that postulated for Sub-facies NA-1. Tests of A-form *Nummulites* are flatter than in the underlying facies (*D*/*T* average of 3·34 compared with 2·64 in Sub-facies NA-1), indicating deepening. The presence of elongate *Discocyclina* may also reflect increased water depth, although they are likely to be allochthonous, for reasons noted earlier.

Studies of the ecology of living LBF reinforce this interpretation. Several researchers (e.g. Leutenegger, 1977; Hottinger, 1982, 1997) showed that the relative abundance of sexually produced, microspheric ('B') forms increases with increasing water depth, and is highest over an intermediate interval of a specific depth range. This is probably related to problems associated with sexual reproduction in hydrodynamically stressed zones (e.g. shallow, turbulent water). Leutenegger (1977) suggested that, as water depth increases, reproduction strategies change from apogamic schizogony in shallow, turbulent water (the process which may have been responsible for the dominance of A-forms in the underlying Facies NA-1), to a biphasic alternation of asexual and sexual generations.

Interpretation of Sub-facies NC2-2

Nummulithoclastic debris packstones of Sub-facies NC2-2 are interbedded with Sub-facies NB-1. The presence of abundant micrite, occasional planktonic foraminifera, and rare sharks' teeth implies deposition in an open marine environment largely unaffected by waves and currents. However, the occurrence of abundant nummulithoclastic debris indicates extensive transportation and suggests periodic high-energy events (the origin of such debris is considered in detail later as part of a wider consideration of

re-sedimented *Nummulites* facies within the Djebel Ousselat facies association).

The shallow-water origin of some of this sediment is indicated by the presence of rare ovate *Discocyclina* and bioeroded ?coral fragments. Biofabrics indicative of both biogenic reworking (e.g. 'sub-horizontal stacking' and 'tangential circular') and high-energy, hydrodynamic influences (e.g. 'contact imbrication' and 'chaotic stacking'; see Fig. 5) suggest that, after deposition, the transported sediments were modified by burrowing organisms.

To summarize the Djebel Afair facies association, Facies DA represents nearshore, quartz-rich, sheet-like sandbodies, which migrated across extensive areas of the inner ramp environment under the influence of tidal currents and waves. Basinward-directed foresets suggest that ebb flow may have been the dominant tidal current. Communities of A-form *Nummulites* (Sub-facies NA-1) later flourished in this very shallow marine setting, before deepening of the water led to the deposition of B-form *Nummulites* communities (Sub-facies NB-1) in a mid-ramp environment, with sedimentation occasionally interrupted by the deposition of re-sedimented nummulithoclastic and other bioclastic debris.

Kesra facies association

The Kesra Plateau is located at the western end of the studied area (see Fig. 7). Various lines of evidence support the view that the plateau was a palaeohigh during the Ypresian, formed by a swell of Upper Cretaceous Abiod Fm limestones, the upper contact of which is a bored hardground. Grocott *et al.* (1998) suggested that the absence of the Palaeocene El Haria Fm, which usually overlies the Abiod Fm, and the reduced thickness of the El Garia Fm are strong evidence for deposition on top of a topographic high. The upper Abiod surface across the palaeohigh exhibits variable relief of at least several metres, possibly much higher locally. The El Garia Fm at this location is of highly variable thickness, reaching a maximum of *ca* 15 m. Facies exposed on the Kesra Plateau, and the relationships between them, are illustrated in Fig. 9.

Interpretation of Facies CH (Sub-facies CH-1 and CH-2)

The bioturbated, smaller benthic foraminiferal (SBF) wackestones of Facies CH comprise the early Eocene Chouabine Fm. The presence of finely comminuted calcite (fine nummulithoclastic debris?) and rare *Nummulites* fragments within Sub-facies CH-2 may represent a transition between the Chouabine Fm (i.e. the nodular Sub-facies CH-1) and the overlying El Garia Fm.

Smaller benthic foraminiferal communities from both sub-facies (see Table 1) are typical of shallow, open marine conditions, below fair-weather wave base (FWWB) (20–50 m?). The SBF assemblage from the younger Sub-facies CH-2 may indicate an increase in water depth after deposition of Sub-facies CH-1 (BouDagher-Fadel, 1988). The abundance of carbonate mud also suggests deposition below the influence of wave and current action. The presence of glauconite, both as re-worked pellets and within the tests of SBF, suggests condensed sedimentation across the palaeohigh. Co-occurrence with phosphate, which indicates high nutrient flux, often associated with upwelling (Parrish *et al.*, 2001) suggests formation in two different marine environments and subsequent re-working (Bolle *et al.*, 1999).

Interpretation of Facies DC (Sub-facies DC-1 and DC-2)

The presence of significant quantities of carbonate mud and glauconite within Sub-facies DC-1 indicates deposition in open marine conditions, below the influence of waves and currents. This interpretation is further reinforced by the presence of abundant elongate *Discocyclina*, suggestive of deposition under low light conditions, and also by the flattened tests of *in situ Nummulites* (average A-form D/T 4·05). Biofabrics such as 'isolated chaotic' and 'tangential circular' within Sub-facies DC-1 are redolent of sediment disturbance by infaunal organisms, including traces reminiscent of those produced by spatangoid echinoids (e.g. Bromley & Asgaard, 1975; Thayer, 1983; see Fig. 5).

However, features of the overlying Sub-facies DC-2 appear to suggest an increase in water energy, probably reflecting a relative fall in sea level. Biofabrics such as 'chaotic stacking' and 'contact imbrication', and the occasional presence of probable scoured surfaces, reflect the increasing influence of waves and currents. Shallowing is also suggested by poorly defined tabular(?) cross-bedding and a marked decrease in mud content in Sub-facies DC-2.

Larger benthic foraminifera tests (particularly *Discocyclina*) in Sub-facies DC-1 are commonly fragmented, whilst those in the overlying Sub-facies DC-2 are generally intact, possibly reflecting

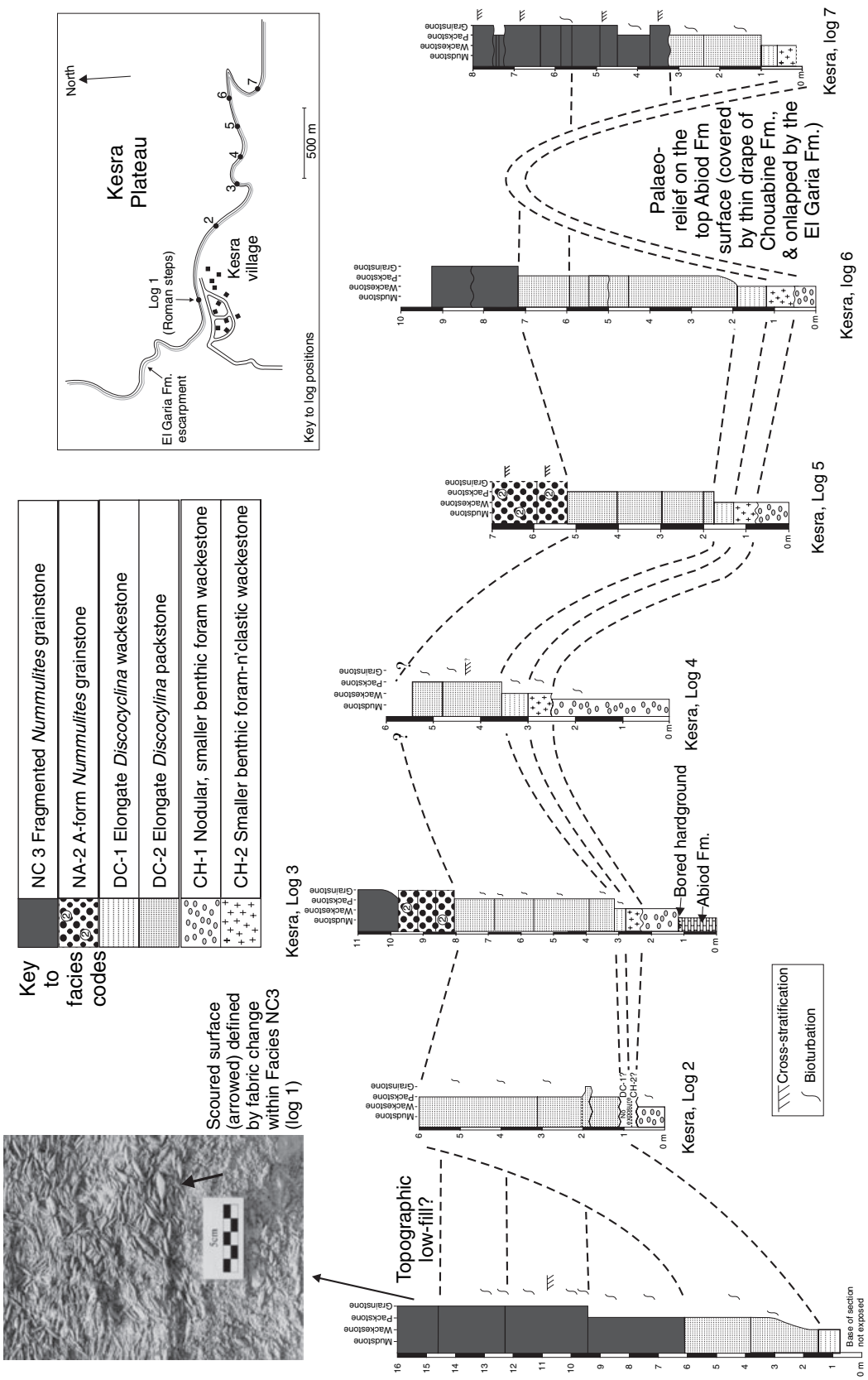

Fig. 9. Kesra facies association.

differences in sedimentation rate. Slower sediment accumulation during deposition of Sub-facies DC-1 resulted in long residence times within the 'taphonomically active zone' (TAZ) and hence increased breakage. In contrast, abandoned tests in Sub-facies DC-2 were rapidly buried and preserved intact. Largely pristine LBF tests within clearly defined *Thalassinoides* burrows in Sub-facies DC-1 suggest that rapid burial (and hence removal from the TAZ) prevented further disintegration. The mechanism of test disintegration is uncertain, as, in common with all LBF examined during this study, micro- and macro-boring are conspicuous by their absence (for a discussion of possible reasons for this see Beavington-Penney, 2004).

Sub-facies DC-1 has similarities with the observations of Houbolt (1957; quoted in Purser, 1973), who noted that the upper surfaces of isolated platforms 'deeply' submerged below FWWB in the Persian Gulf are covered by sediment rich in large perforate foraminifera. He observed that such platforms are characterized by sediment 'storage', with little material being swept off into the surrounding deeper water.

Interpretation of Facies NC3

Nummulites from Facies NC3 exhibit a range of test damage from partial to almost complete fragmentation, probably reflecting abrasion during transportation. Sediment transport is suggested by biofabrics indicative of strong currents, occasional scoured surfaces (see Fig. 9), and also the presence of trough(?) and tabular cross-bedding. Palaeocurrent directions obtained from the cross-bedding suggest transport towards the NW/NE, which may correlate with the 'major' NW-flowing oceanic currents noted by Zaïer *et al.* (1998) to have affected the basins to the east/NE of Kasserine Island. Studies of modern topographic highs affected by oceanic currents note acceleration of the currents because of constriction as they impinge on the highs (e.g. Hallock *et al.*, 1988; Triffleman *et al.*, 1992; Tsuji, 1993), and appear to present a plausible mechanism for sediment transport across the Kesra palaeohigh. Active hydrodynamic conditions are also suggested by wave-produced biofabrics and possible tubular tempestites (cf. Tedesco & Wanless, 1991, 1995), produced by storm-infilling of open-burrow networks, which indicate that storms periodically swept the platform top.

Taphonomic study of *Nummulites* from this facies raises a number of questions about sediment transport mechanism(s). Experimental and field observations (see Beavington-Penney, 2004) suggest that, whilst *Nummulites* were relatively easily entrained, they were more likely to be transported as part of a bedload 'traction carpet'. The findings of Beavington-Penney (2004) also indicate that such transport is extremely inefficient at fracturing tests and suggest that the observed damage could be the result of slow, partial dissolution of tests and the effects of predatory fish and echinoids ('foraminiferivory'). Purser (1973) noted that modern isolated platforms in the Persian Gulf whose tops are close to FWWB, are highly susceptible to sediment transport, whilst those whose tops are significantly shallower than FWWB experience much slower sediment transport rates. The latter scenario likely reflects the situation at Kesra during deposition of Facies NC3, with *Nummulites* test damage being facilitated by slow transport rates, and hence long residence times on the platform top. The likelihood that water depths across the Kesra high were very shallow during deposition of this facies is reinforced by diagenetic evidence (Jorry *et al.*, 2003) of occasional, localized subaerial exposure of the El Garia Fm across the high.

An analogy can be drawn with Serranilla Bank, an modern isolated platform submerged at least 10 m below the sea surface on the Nicaraguan Rise. As noted by Hallock *et al.* (1988) and Triffleman *et al.* (1992), Serranilla Bank is strongly influenced by waves and currents, with the mud-poor sediment cover accumulating on the leeward margin and ultimately being shed into the adjacent basin. The platform is a site of active sediment production, and, because it lacks a reefal rim (as was the case at Kesra), is also a site of extensive sediment export. Thus, it seems likely that much of the nummulitic sediment produced on the Kesra High was ultimately 'exported' into the surrounding, deeper water parts of the basin.

Interpretation of Sub-facies NA-2

The A-form nummulitic grainstones of Sub-facies NA-2 lack the coarse-grained quartz, ovate *Discocyclina* and cross-bedding typical of Sub-facies NA-1. However, as with Sub-facies NA-1, the 'robust' nature of *Nummulites* tests (average A-form D/T 2·84), combined with wave-produced biofabrics and the presence of patches of micrite, suggests that this sub-facies represents a winnowed, parautochthonous accumulation that was deposited in a very shallow, open marine environment, possibly close to FWWB. The absence of

coarse-grained quartz probably reflects deposition on the Kesra High, isolated from the emergent areas that sourced the quartz present in Sub-facies NA-1 at Djebel Afair. Palaeoecological differences between these two environments may also account for the lack of ovate *Discocyclina* in Sub-facies NA-2. Elongate *Discocyclina* within this facies may be allochthonous, because of the ease with which their thin, flat tests were probably entrained.

The reason for preservation of approximately *in situ Nummulites* gravels in an environment characterized by extensive fragmentation and transportation (as discussed within in the section Interpretation of Facies NC3, above) is unclear. They may have been filling topographic lows, where they were protected to a degree against re-working. The gravels do suggest that the bulk of the sediment produced on the Kesra High, and thus the sediment shed into the surrounding basin, was comprised of A-form *Nummulites*.

To summarize the Kesra facies association, following deposition of the condensed sediments of the Chouabine Fm (Facies CH) below FWWB (20–50 m?), communities of *Nummulites* and *Discocyclina* (Facies DC) flourished across the bathymetric high. Sub-facies DC-1 appears to represent deposition in low-light conditions below FWWB (>50 m?), whilst the overlying Sub-facies DC-2 was mostly deposited during a relative sea level fall (which brought the top of the Kesra High close to FWWB). Further relative sea level fall increased water energy levels across the platform top, and resulted in the production of abundant robust, megalospheric *Nummulites* (Sub-facies NA-2 and Facies NC3), which were transported across the platform and 'exported', in a largely fragmented state, into the adjacent deeper water areas of the basin.

Djebel Ousselat facies association

As shown in Fig. 7, several facies are common to the remaining areas examined during this study (Kef Guitoune and El Garia village), and have been combined into the Djebel Ousselat facies association. At Kef Guitoune, a vertical cliff exposes a 130 m thick package of El Garia Fm. At the base of the cliff the Ypresian deposits are thrust over Oligocene sediments (Rigane *et al.*, 1994); neither the basal nor upper contacts of the El Garia Fm are exposed. The El Garia Fm is composed of stacked, sheet-like beds (see Fig. 10), which are generally 1–3 m thick, and can be traced laterally down the depositional dip for several km. At the village of El Garia, *ca* 8 km ESE of Kesra (see Fig. 7), a thinner (35 m) package of the El Garia Fm. is exposed, which dips steeply towards the SE, and is locally overturned. Facies exposed at Kef Guitoune and El Garia village, and the relationships between them, are illustrated in Figs 10 and 11, respectively.

Interpretation of Facies NC3

Fragmented *Nummulites* grainstones and packstones of Facies NC3 have been described earlier from outcrops at Kesra. Whilst exposures of this facies at both Kef Guitoune and El Garia village share the broad characteristics of those on the palaeohigh, their markedly different depositional environment and possible variations in re-sedimentation mechanism make it useful to consider them separately.

As at Kesra, biofabrics indicative of hydrodynamic re-working, and the fragmented nature of many *Nummulites* tests, imply extensive transport. However, whether that transportation occurred as rapidly deposited turbidity flows sourced from Kesra and other possible topographic highs, as previously suggested by Moody & Grant (1989) and Racey *et al.* (2001), or was driven by oceanic or storm currents over an extended period of time, is uncertain. When compared with unquestionable nummulitic turbidites, such as those of the southern Pyrenean foreland basin (Beavington-Penney, 2004), the degree of *Nummulites* test damage observed in Facies NC3 closely resembles that observed in many calci-turbidites (such as breakage of the marginal cord of the penultimate, and younger, whorls, and fracturing throughout the entire test thickness). However, there are numerous dissimilarities, including the presence of common bioturbation features, often throughout their entire thickness. Unfortunately, there are inherent difficulties associated with definitively identifying turbidites within the El Garia Fm, related to the extremely sparse fauna of the El Garia Fm. The composition of calci-turbidites can be highly variable, depending on the inter-relationships between factors such as sea level, platform geometry and prevailing wind direction (e.g., Eberli, 1987; Haak & Schlager, 1989; Tucker & Wright, 1990; Schlager *et al.*, 1994). Whilst turbidites shed from shallow, submerged topographic highs (such as Kesra) might be expected to contain platform top and slope biota, the sparse, often monogeneric fauna of the El Garia Fm makes it hard to determine whether such mixed bioclast assemblages are present. This sparse fauna further complicates identification of *Nummulites*-bearing

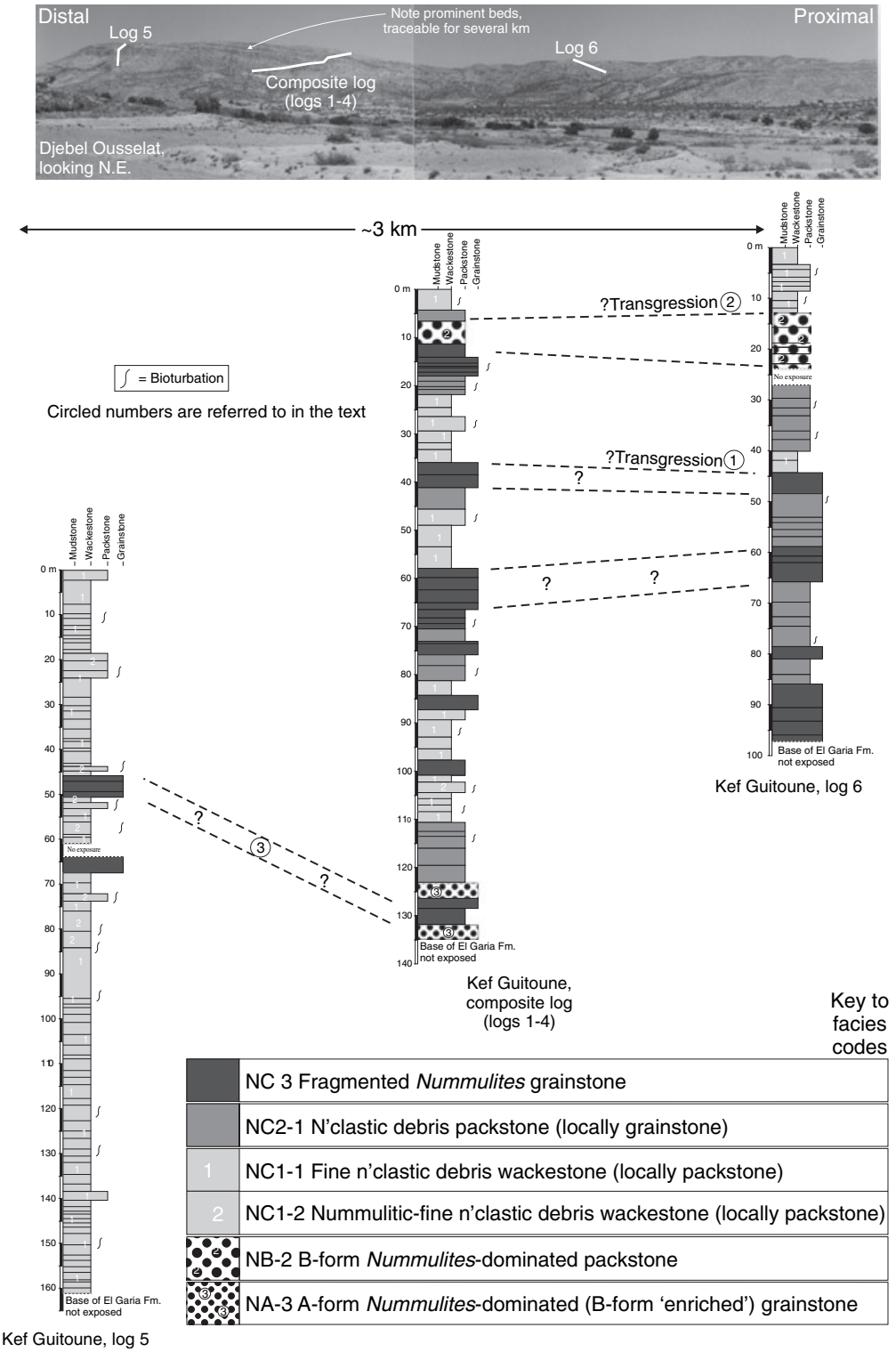

Fig. 10. Djebel Ousselat facies association (at Kef Guitoune).

'event' beds in the El Garia Fm. because there is little or no contrast with the surrounding 'host' sediments, which may themselves be re-sedimented. We provisionally suggest that a combination of the two mechanisms may be responsible, with sediment exported into the basin by storm (and other) currents and periodic turbidity flows, with the characteristics of the resulting deposits being altered by subsequent biological and hydrodynamic modification.

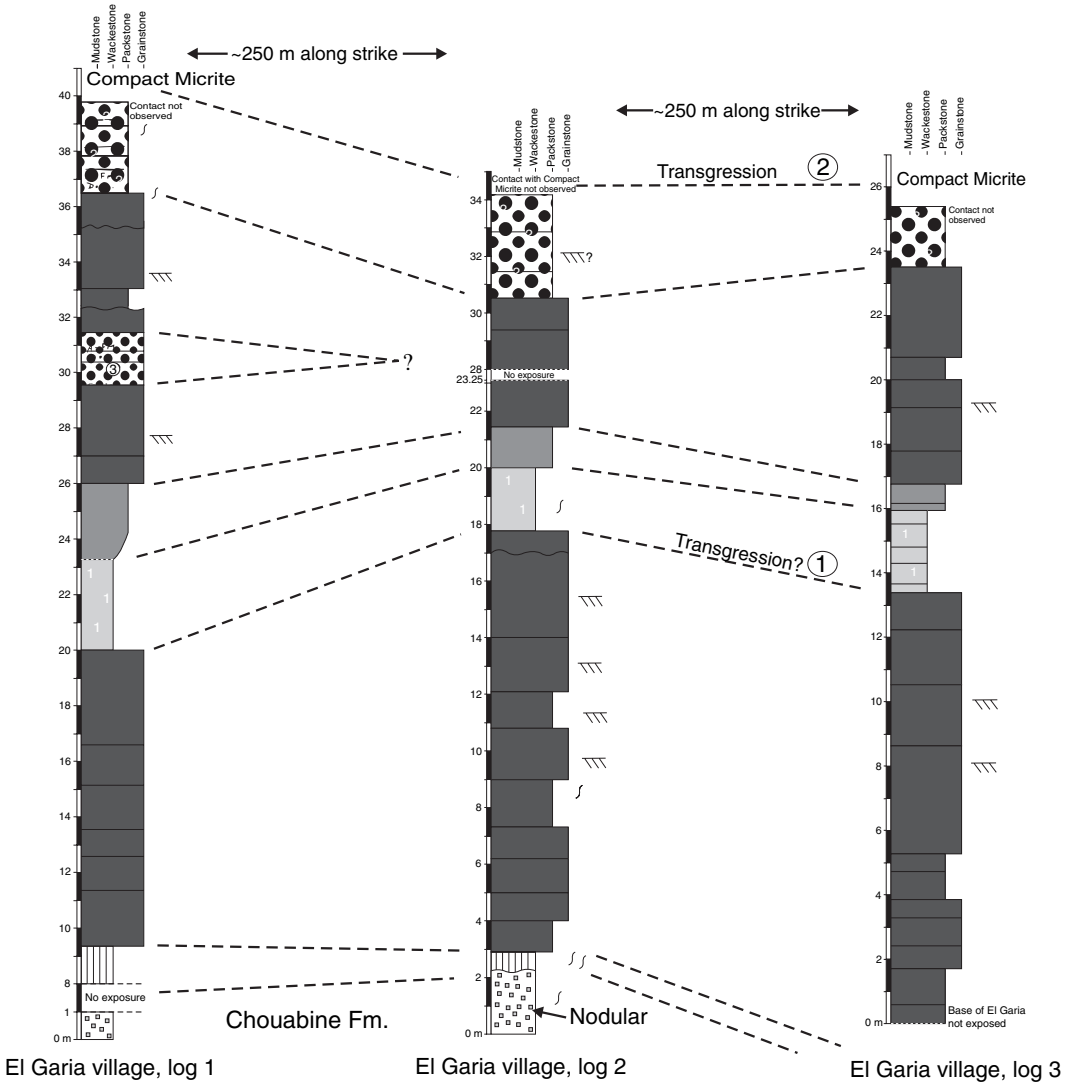

Fig. 11. Djebel Ousselat facies association (at El Garia village).

Interpretation of Facies NC1

The well-sorted wackestones and packstones of finely comminuted *Nummulites* debris of this facies comprise the Ousselat Member of the El Garia Fm, a transitional facies between the El Garia Fm and the Bou Dabbous Fm.

An abundance of micrite, the presence of occasional planktonic foraminifera, and common

bioturbation-produced biofabrics suggest that this facies was deposited in an open marine environment, below the influence of storm- or tide-induced currents. A-form *Nummulites* are found throughout this facies, most notably within Sub-facies NC1-2, generally preserved as parautochthonous or allochthonous accumulations, either back-filled into burrows (see Fig. 6F), or swept into open burrows during storms (i.e. 'tubular tempestites'; cf. Tedesco & Wanless, 1991, 1995). Their flattened tests (average A-form *D*/*T* 7·42) suggest that these represent a community living in oligophotic conditions close to or below storm wave base (SWB). The presence of this megalospheric *Nummulites* community may be related to reproduction strategy: asexual reproduction seems to dominate in highly stressed environments (e.g. very shallow or deep water where high or low light levels, respectively, inhibit photosynthesis; Leutenegger, 1977).

As discussed earlier, the experiments described in Beavington-Penney (2004) suggest that *Nummulites* were extremely resistant to abrasion. Thus, abrasion resulting from very long transport times and/or distances, perhaps in conjunction with the effects of predatory fish and echinoids, and possibly slow dissolution, are probably candidates for production of the sand- to silt-sized broken *Nummulites* fraction observed in this facies. However, the fine grain size and degree of sorting may also in part result from the activity of burrowing crustaceans. In modern carbonate environments, crustaceans (especially shrimps) create extensive burrow networks in a wide variety of environments, ranging from tidal flats (Shinn, 1968) to fore-reef slopes down to at least 150 m (Tedesco & Wanless, 1991), and their influence on comparable Tertiary sediments has also been documented (e.g. Taberner & Bosence, 1995; Pedley, 1998). Certain taxa of shrimp (e.g. *Callianassa*) have been shown to sort sediment as they burrow, preferentially ejecting the fine (<1 mm) fraction onto the seafloor, and back-filling the chambers of their burrows with the coarser fraction (Tudhope & Scoffin, 1984). This results in a layer of fine sediment at the surface, which, because of the ease with which it is entrained, is normally not preserved *in situ*. Bradshaw & Scoffin (2001) note that this recycling of fine grains to the surface also results in accelerated disintegration of the fine sediment fraction because of increased time spent within the TAZ. It seems probable that this process, combined with the other taphonomic processes described above, was largely responsible for the creation of the Ousselat Member, as illustrated in Fig. 12.

Interpretation of Sub-facies NC2-1

Re-sedimented 'nummulithoclastic debris' packstones (and rarely grainstones) of this facies have already been documented from Djebel Afair (Sub-facies NC2-2); Sub-facies NC2-1 at Kef Guitoune and El Garia village differs from the former in variations of the non-*Nummulites* bioclastic content, which likely reflect differences in provenance of re-sedimented material. The dominance of nummulithoclastic debris (i.e. the >0·2 mm to <1·3 mm size fraction of broken *Nummulites*) suggests that it is transitional between the coarser fragmented *Nummulites* debris of Facies NC3 and the finely comminuted *Nummulites* debris of Facies NC1.

Interpretation of Sub-facies NA-3

The A-form *Nummulites*-dominated grainstones of this sub-facies are distinguished from Sub-facies NA-1 and NA-2 in terms of differences in A- to B-form ratio, the absence of ovate *Discocyclina*, coarse-grained quartz and cross-bedding (seen in Sub-Facies NA-1), and associated facies.

As with Sub-facies NA-1 and NA-2, the 'robust' nature of the A-form *Nummulites* tests (average A-form *D*/*T* 2·64), combined with wave- and current-produced biofabrics, and the presence of rare patches of micrite, suggests that this sub-facies represents a winnowed, parautochthonous accumulation that was deposited in a very shallow, open marine environment. However, the increased proportion of microspheric forms (the A- to B-form ratio varies between 6 : 1 and 9 : 1) may indicate deposition in deeper water than that postulated for the previous two sub-facies.

Interpretation of Sub-facies NB-2

The B-form *Nummulites*-dominated packstones of this sub-facies are differentiated from Sub-facies NB-1 largely on the basis of an absence of medium- to coarse-grained quartz, probably reflecting their deposition remote from emergent areas.

The predominance of B-forms suggests deposition below FWWB, as discussed within the interpretation of Sub-facies NB-1. This is reinforced by the flattened tests of A-forms (average A-form *D*/*T* 3·33) and the presence of abundant micrite. Biofabrics such as 'contact imbrication', 'chaotic stacking' and 'linear accumulation' indicate that energy levels were periodically high enough to affect the sea floor, whilst 'sub-horizontal stacking' biofabrics and the presence of

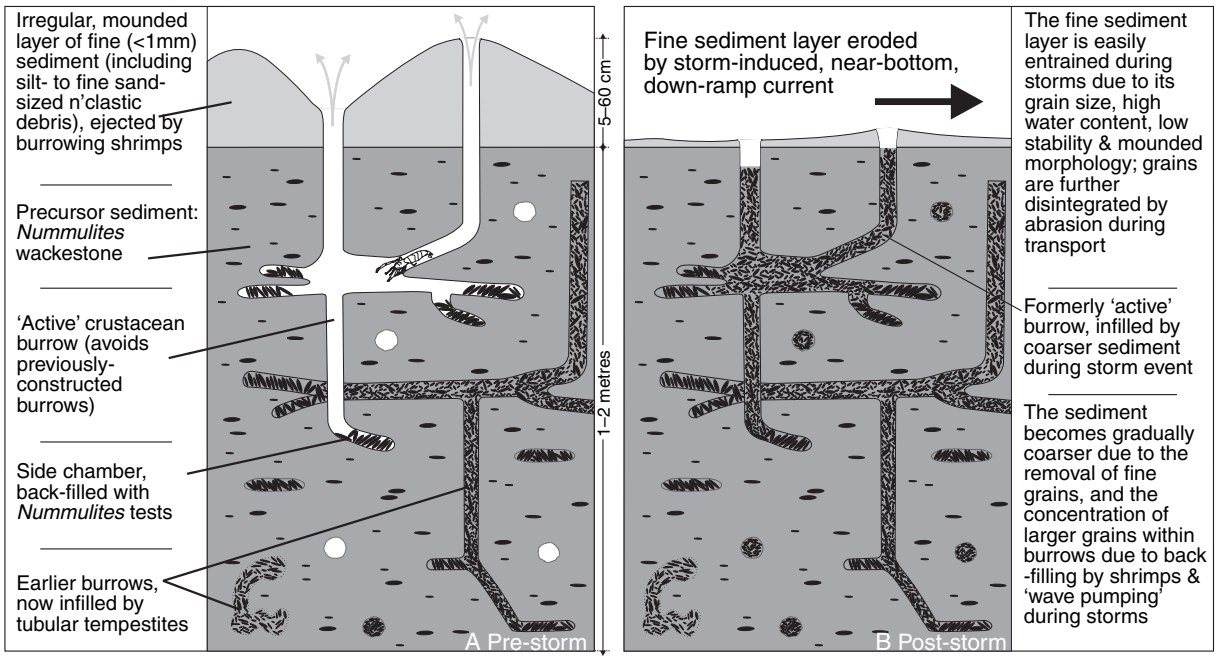

Fig. 12. The proposed mechanism responsible for the creation of the distal Ousselat Member of the El Garia Formation: (a) preferential ejection of the fine (<1 mm) sediment fraction from crustacean burrows results in the creation of a thin, mounded layer composed, in part, of fine nummulithoclastic debris. Accelerated biological, mechanical and chemical disintegration of this fine fraction occurs due to the length of time it spends in the 'taphonomically active zone'; (b) this layer is easily entrained during storms, and is deposited in more distal parts of the ramp. Diagram constructed using information from Shinn (1968); Aller & Dodge (1974); Tudhope & Scoffin (1984); Wanless *et al.* (1988); Tedesco & Wanless (1991); Bradshaw & Scoffin (2001), and this study.

probable crustacean fragments suggest that the community was disturbed by bioturbation. Thus, this sub-facies appears to represent a para-autochthonous *Nummulites* community, most likely living in a mesophotic environment below FWWB.

Interpretation of Sub-facies CH-3 and DC-3

Sub-facies CH-3, which is exposed at El Garia village, is considered to be the lateral equivalent of Sub-facies CH-1 identified at Kesra. As it is, in almost all respects, identical to CH-1 (being differentiated on the presence of occasional gastropods and probable bivalves, which have been replaced by non-ferroan calcite spar), the characteristics of this facies will not be described again. As at Kesra, it is considered to represent condensed sedimentation during a marine transgression. Unlike at Kesra, Sub-facies CH-2 is absent; instead CH-3 is directly overlain by Sub-facies DC-3. This is interpreted as having the lateral equivalent of Sub-facies DC-1 exposed at Kesra, although reduced numbers of elongate *Discocyclina* and *Nummulites* (when compared with Sub-facies DC-1) may be a consequence of deposition in relatively deeper water.

To summarize the Djebel Ousselat facies association, deposition of the El Garia Fm. at Kef Guitoune and El Garia village was dominated by re-sedimentation of *Nummulites* from adjacent palaeohigh(s), probably by turbidity flows and oceanic/storm currents. Extensive hydrodynamic and biological re-working resulted in a proximal to distal trend of increasingly fine *Nummulites* debris. Relatively minor *in situ* sediment production resulted from B-form *Nummulites*-dominated (or 'enriched') communites in the shallower, relatively proximal parts of the basin, and A-form communities in the deeper (outer ramp) parts of the basin. Biofabric analysis of the El Garia Fm from the Djebel Ousselat facies association (Beavington-Penney, 2002) suggests that much of this sediment does not reflect original fabric and stratification at the time of deposition, but is largely the product of extensive 'bio-retexturing' by burrowing organisms.

We speculate that the reduced thickness of largely allochthonous sediments at El Garia village represents a transition between the *Nummulites* 'factory' on the palaeohigh (e.g. the Kesra facies association) and sediment 'sinks' in the adjacent deeper areas of the basin (e.g. at Kef

Guitoune). This reduced thickness may be the result of bypassing as sediment moved down the slope towards the surrounding deeper water.

Evidence for sea-level change during deposition of the Djebel Ousselat facies association is either absent or poorly constrained. For example, at Kef Guitoune, one regressive and two transgressive events can be postulated. The two possible flooding events (marked '1' and '2' in Fig. 10) are indicated by the occurrence of the relatively deep water (approximately SWB?) Facies NC1 in the most proximal part of the studied section (log 6). The regressive event ('3' in Fig. 10) is suggested by the occurrence of coarse *Nummulites* fragments of the relatively proximal Facies NC3 in the more distal parts of the section. At El Garia village, two distinct transgressive events are present, indicated by the occurrence of Facies NC1 inter-bedded with the more proximal Facies NC3 ('1' in Fig. 11), and the 'Compact Micrite' overlying the El Garia Fm ('2' in Fig. 11), which represents a significant regional flooding event (Racey *et al.*, 2001).

AN INTEGRATED DEPOSITIONAL MODEL

The interpretations of the three distinct facies associations have been integrated into an overall depositional model (Fig. 13). As noted in the Introduction, the broad depositional setting for the El Garia Fm is well understood (Fournie, 1975; Moody, 1987; Loucks *et al.*, 1998; Zaïer *et al.*, 1998). Our study indicates that *Nummulites* production (dominated by A-forms) across this ramp was at its highest over very shallow, submerged palaeohighs. High water energy levels and the lack of a sediment-retaining reefal rim meant that this sediment could not be 'stored' on these highs. Rather, sediment was exported into the surrounding deeper water, where extensive hydrodynamic and biological reworking resulted in a proximal to distal trend of increasingly fragmented *Nummulites* (i.e. the Djebel Ousselat facies association). This is illustrated by pie charts in Fig. 13, showing changes in facies proportions down the depositional dip. Away from the palaeohighs, relatively minor *in situ* sediment production resulted from the increased abundance of B-form *Nummulites* in mid-ramp settings, and elongate A-forms in the outer ramp. Extensive 'bio-retexturing' by burrowing organisms largely destroyed the original fabric and stratification of mid-ramp to outer ramp sediments.

High rates of A-form *Nummulites* production also occurred in very shallow, nearshore areas. Evidence from Facies DA and Sub-facies NA-1 suggests that this sediment was not transported offshore: these facies are unique in that they contain coralline red algae and ovate *Discocyclina*, neither of which have been identified in any of the other studied deeper water sections. As both are relatively resistant to abrasion and are easily entrained (e.g. Testa & Bosence, 1998), this suggests that sediment deposited in nearshore settings was perhaps trapped by a 'littoral energy fence', and was not exported to deeper ramp settings.

Palaeoclimatic models (e.g. Valdes *et al.*, 1999) indicate that deposition of the El Garia Fm occurred on a windward ramp. This provides a possible mechanism for the transport of *Nummulites*, as windward ramps tend to be characterized by offshore and lateral (i.e. longshore) transport (Aurell *et al.*, 1998), with onshore-directed storm winds compensated by a near-bottom return current that flows offshore, often enhanced by ebb-tidal currents (Aigner, 1985). The effectiveness of such processes has been illustrated by Aurell *et al.* (1995), who calculated basinward sediment transport distances of 25–40 km on Oxfordian and Kimmeridgian ramps, and by Purser (1973), who noted that transport of sediment from modern bathymetric highs in the Persian Gulf has resulted in fine sand and silt sediment 'tails' up to 15 km long in their lee. Such processes, probably in combination with 'major' oceanic currents (Zaïer *et al.*, 1998), may have affected the area to the east/NE of Kasserine Island, resulting in offshore transportation (and associated fragmentation) of *Nummulites* and other sediment from very shallow water 'factories' on bathymetric highs.

Although our model agrees with the broad depositional setting for the El Garia Fm mentioned above, it differs from several recently published models in terms of sediment dynamics on the ramp. For example, recent researchers concluded that *Nummulites* production across the ramp was highest in mid-ramp environments, and was at its lowest over palaeohighs, where condensed sections formed (e.g. Loucks *et al.*, 1998; Vennin *et al.*, 2003). Despite the fact that numerous studies have not noted any prominent hierarchical cyclicity or widespread correlateable surfaces within the El Garia Fm (e.g. Loucks *et al.*, 1998; Racey *et al.*, 2001; Jorry *et al.*, 2003), a recent high-resolution sequence stratigraphic model of the mid-ramp to outer ramp El Garia Fm sediments at Djebel Ousselat (Vennin *et al.*, 2003) has

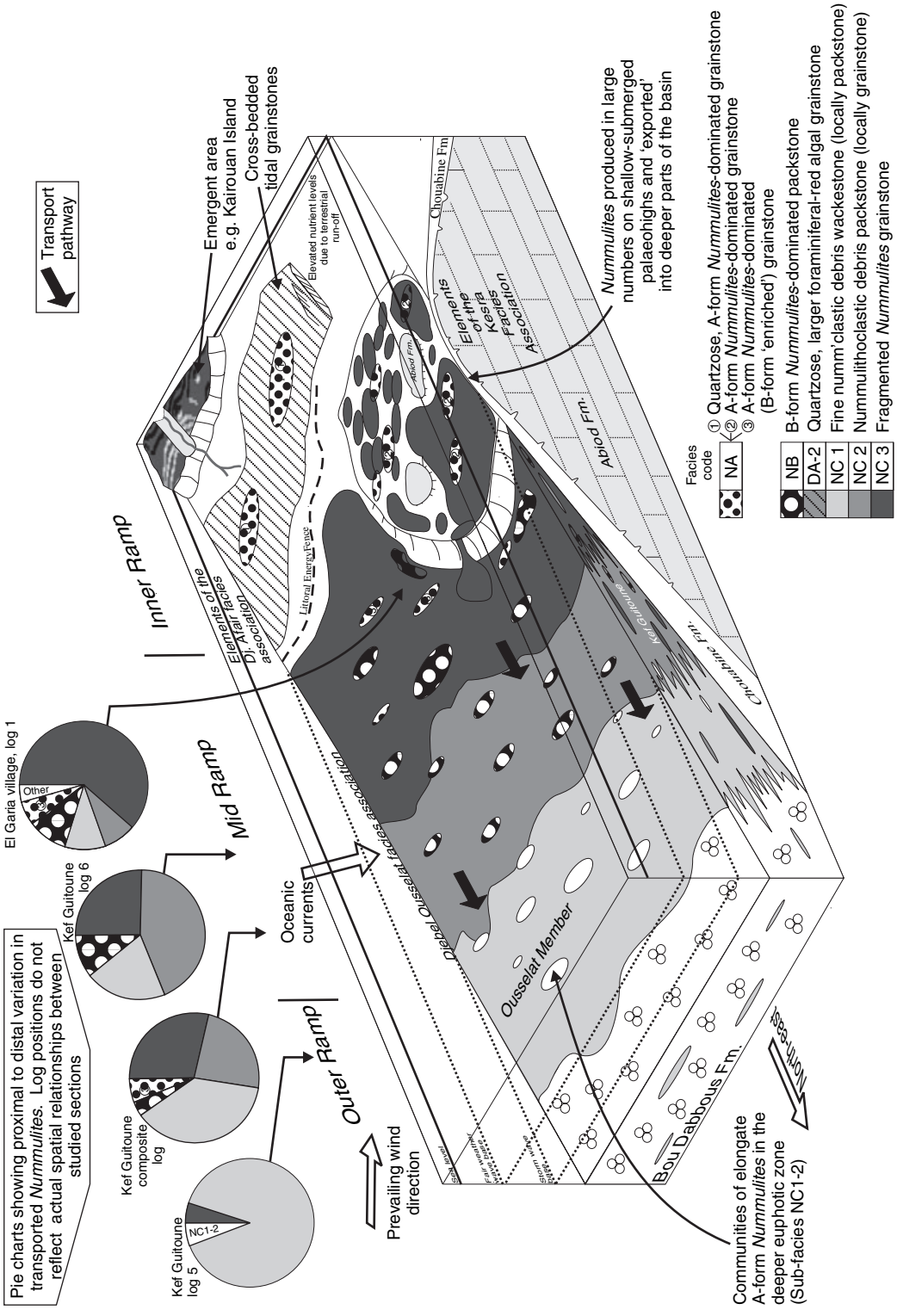

Fig. 13. Generalized depositional model for the El Garia Fm, based on outcrop study, north-central Tunisia.

identified a hierarchy of cycles (to the resolution of individual Milankovitch cycles), interpreted as reflecting a nested hierarchy of sea-level change.

Resolving these issues of sediment production and dispersal patterns on the ramp is important for our understanding of the development of the El Garia Fm, and for early Tertiary carbonate platforms generally, and also has economic significance, as such models are being used to construct reservoir models for the El Garia Fm and other nummulitic limestones. These issues, and also the sequence-stratigraphic context of the El Garia Fm, are discussed in more detail below.

SEDIMENT DYNAMICS ON EARLY TERTIARY, *NUMMULITES*-DOMINATED RAMPS

Despite the importance of *Nummulites* as sediment contributors in Eocene, circum-Tethyan limestones, current understanding of the location of the *Nummulites* 'factory' is controversial. Whilst they occupied a broad range of water depths within the photic zone (Racey, 2001), there is a general consensus that *Nummulites* accumulations represent high production rates in mesophotic (i.e. mid-ramp) waters (e.g. Moody & Grant, 1989; Loucks *et al.*, 1998; Luterbacher, 1998; Pomar, 2001; see Fig. 14A). However, other studies (particularly the earliest models) of *Nummulites* accumulations suggest that much of the sediment was produced in shallower, wave-influenced, euphotic water (e.g. Arni & Lanterno, 1972, 1976; Decrouez & Lanterno, 1979; Sinclair *et al.*, 1998; see Fig. 14B,C). Allen *et al.* (2001) used the reef coral-derived depth-dependent photosynthesis function of Bosscher & Schlager (1992) to model accumulation of the Eocene nummulitic limestones of the Alpine foreland basin. Other authors have suggested that the *Nummulites* factory was more broadly spread through the upper photic zone, with production occurring in both the inner and mid-ramp (i.e. euphotic and mesophotic) zones (e.g. Gilham & Bristow, 1998; Racey, 2001).

Recent quantitative studies of carbonate production by modern LBF have shown that they are capable of producing large volumes of $CaCO_3$ in shallow marine environments, reinforcing the conclusion that the Eocene *Nummulites* 'factory' was located in very shallow water. For example, Fujita *et al.* (2000) showed that $CaCO_3$ production by *Marginopora kudakajimensis* in 1 m deep water around the Ryukyu Islands (NW Pacific) may be as high as 5 kg m^{-2} $year^{-1}$. Numerous other studies have also demonstrated very high standing crops and prolific carbonate sediment production in shallow water by LBF (summarized in Table 2). Such figures may be low compared with those of the Cretaceous and Palaeocene, when $CaCO_3$ production was possibly much higher – a consequence of atmospheric CO_2 levels and low Mg/Ca ratio (Stanley & Hardie, 1998). Although very little has been published on the production rates of modern larger foraminifera in deeper water environments, the existing data suggest that sediment production decreases markedly with depth. For example, accumulation rates for autochthonous, nummulitid-bearing larger foraminiferal sands on the middle and outer Queensland Shelf (in water depths of 30–65 m; Tudhope & Scoffin, 1988), are an order of magnitude lower than the accumulation rates of autochthonous LBF sands in much shallower (2·5–10 m) water in lagoons and on the reef flat and slope in Palau (western Caroline Islands) (Hallock, 1981). Such data indicate that LBF production profiles are similar to (albeit 30–40% lower than) Holocene corals (which show maximum growth rates of *ca* 12·5 mm $year^{-1}$; Bosscher & Schlager, 1992; Schlager, 1999).

This strongly depth-dependent carbonate production, with high production rates in shallow water, has led to the formation of steep-margined platforms in the late Cenozoic (Schlager, 1981; Bosscher & Schlager, 1992; Bosence *et al.*, 1994). However, ramp-like geometries are commonly observed in studies of Tertiary, circum-Tethyan, larger foraminiferal limestones (e.g. Loucks *et al.*, 1998; Pedley, 1998). Development of such 'layer cake' stratal packages in mid to outer ramp environments is most likely the product of two processes: decreased differentiation of depth-dependent production rates (Wright & Faulkner, 1990; Burchette & Wright, 1992), and/or strong offshore transport (Aurell *et al.*, 1995, 1998). Accumulation patterns of recent LBF are strongly influenced by the transportation of living and dead tests (Hallock, 1981; Li *et al.*, 1998). Similarly, *Halimeda* often accumulates remote from where it was produced because its plate-shaped grains are easily entrained (Wray, 1977). Similar processes acting during the early Tertiary may have masked the real occurrence patterns of *Nummulites.*

As noted above, earlier models of the El Garia Fm suggested that sediment production by *Nummulites* was lowest in the very shallow water over palaeohighs, with the bulk of the sediment being produced in the surrounding deeper water. For

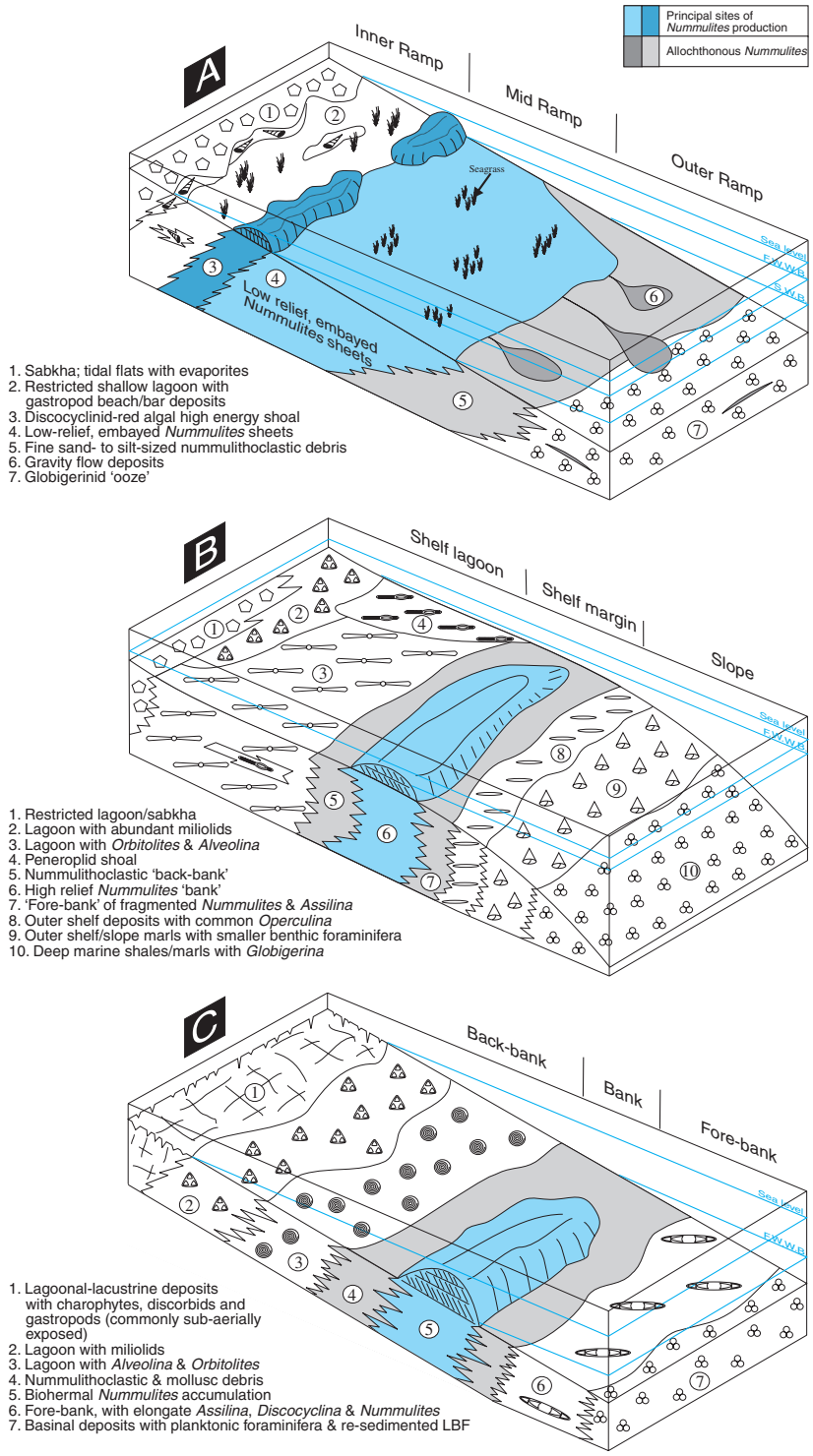

Fig. 14. Examples of earlier models for the depositional setting and facies associations of *Nummulites* accumulations: (A) Depositional model for the Lower Eocene El Garia Fm, modified from Loucks *et al.*, 1998. High *Nummulites* production in mid-ramp settings has also been concluded by Gilham & Bristow (1998) and Luterbacher (1998). (B) Depositional model for Eocene *Nummulites* accumulations of the Sirte Basin, Libya, modified from Arni (1965) (similar shallow water buildups have been noted from winnowed shelf-margins or on the crest of structural/salt domes by Arni & Lanterno, 1972, Aigner, 1983 and Moody, 1987). (C) Depositional model for Eocene *Nummulites* accumulations of Croatia, modified from Bignot (1972) (similar ramp models have been published by Comte & Lehmann, 1974, Fournie, 1975, Serra-Kiel & Reguant, 1984, Buxton & Pedley, 1989 and Sinclair *et al.*, 1998).

example, Loucks *et al.* (1998) concluded that highest production rates for *Nummulites* were in mid-ramp environments, in water *ca* 30–60 m deep, and Vennin *et al.* (2003) suggested that the thin packages of El Garia Fm which crop out on palaeohighs represent stratigraphically complete, condensed sections that can be correlated with the much thicker deposits away from the highs. As shown in Fig. 13, our study of these limestones suggests that $CaCO_3$ production by *Nummulites* was actually at its highest in very shallow, euphotic water, close to or above fair-weather wave base. In both nearshore areas and also on isolated, submerged 'highs', fast-growing, rapidly reproducing megalospheric *Nummulites* thrived and were ultimately 'exported' into the surrounding deeper parts of the basin by a combination of gravity slides and storm current-induced traction carpets. The effectiveness of offshore transport, combined with the effects of bioerosion and biogenic sorting of the sediment, resulted in a distal trend of increasingly fine nummulithoclastic sediment away from the highs. This offshore transport, in conjunction with relatively limited sediment production by deeper-dwelling B-form communities in mesophotic, mid-ramp environments, and also by elongate A-forms in deeper, oligophotic settings, was critical for controlling the ramp-like stratal geometries often observed in the field (e.g. at Kef Guitoune). Thus we disagree with the conclusion of Vennin *et al.* (2003) that the thin packages of El Garia Fm that crop out on top of palaeohighs are condensed, but complete, stratigraphic successions. Rather, we suggest that these outcrops comprise merely a remnant of the large quantities of *Nummulites* that were produced in the very shallow water that covered these highs and 'exported' into the surrounding deeper water. Given this scenario, it is impossible to correlate time-equivalent horizons within the El Garia Fm. between the palaeohighs and more basinal outcrops. Our study, in conjunction with studies of the accumulation patterns of modern larger foraminiferal sediments (e.g. Hallock, 1981; Li *et al.*, 1998), also has implications for the validity of the approach of Allen *et al.* (2001), who used a depth-dependent photosynthesis function based on modern corals to model the accumulation of Eocene nummulitic limestones from the Alpine foreland basin. Although we agree that the sediment production profiles for corals and larger foraminifera are similar, they have very different accumulation profiles, because of the susceptibility of LBF to transportation. As observed by Hallock (1981), translating larger foraminiferal production rates into accumulation rates is more difficult than the equivalent calculation for corals.

The patterns of sediment production and dispersal suggested by this study of the El Garia Fm do not reinforce the high-resolution (third to fifth order) sequence-stratigraphic model of the mid-ramp to outer-ramp El Garia Fm sediments at Djebel Ousselat presented by Vennin *et al.* (2003). Despite the El Garia Fm having been deposited over *ca* 2·8 Myr (Racey *et al.*, 2001), during which time several third-order sea level changes might be expected to have occurred, earlier studies have not noted widespread, correlateable surfaces within the El Garia Fm (such as the Fe-rich hardgrounds which Vennin *et al.*, 2003 record as bounding their fifth-order cycles), or identified any prominent hierarchical cyclicity (e.g. Moody *et al.*, 2001; Racey *et al.*, 2001; Beavington-Penney, 2002; Jorry *et al.*, 2003), and have not presented unambiguous evidence of relative sea-level change. Whilst one study (Loucks *et al.*, 1998) did identify several, poorly defined cycles in some boreholes, these could not be correlated between wells. Vennin *et al.* (2003) claim that their hierarchy of cycles was produced by a nested hierarchy of eustatic sea level change. Although variations in sediment supply unrelated to sea-level change could produce 'cycles' of the type they describe, they do not consider the possibility that some of the sediment may be allochthonous. As demonstrated above, this study of the El Garia Fm, combined with evidence from recent larger foraminifera (e.g. Hallock, 1981; Li *et al.*, 1998), and the recognition of transported *Nummulites* within the El Garia Fm (e.g. Moody & Grant, 1989; Racey *et al.*, 2001), indicates that transport of *Nummulites* was a ubiquitous process, operating a strong control on the development of stratigraphic architecture. It seems most probable that the variations in type and abundance of *Nummulites* likely reflect 'background' sedimentation interrupted by periodic influxes of transported tests, along with other intrinsic processes such as extensive bio-retexturing by burrowing organisms. Low-amplitude (several metres), high-frequency changes in relative sea level, which might be expected to have characterized the Eocene greenhouse period (Read & Horbury, 1993), are unlikely to have overprinted such processes in mid-ramp and outer ramp settings. Evidence of syn-depositional tectonic activity during deposition of the El Garia Fm along the NOSA structural zone (Zaïer *et al.*, 1998; see Fig. 1), reinforced by the conflicting

Table 2. Density and estimated annual $CaCO_3$ production data for selected recent larger benthic foraminifera (nummulitids asterisked).

Foraminifera	Location	Water depth/ environment	Density (expressed as number of tests)	Estimated annual production $CaCO_3$	Reference
Amphistegina sp.	Florida Keys	15–30 m	0·3 to >4 cm^{-2}		Hallock & Talge, 1993
	Oahu, Hawaii	0–10 m	$7{\cdot}11 \times 10^4$ m^{-2}	241 g m^{-2} $year^{-1}$	Muller, 1976
A. madagascariensis	Oahu, Hawaii		Max. $4{\cdot}17 \times 10^5$ m^{-2}	500 g m^{-2} $year^{-1}$	Muller, 1974
A. lobifera	Okinawa, Japan	Reef crest	200 m^{-2}		Hohenegger, 1994
		Frontal reef crest	860 m^{-2}		
		Beach	320 m^{-2}		
A. lessonii	Okinawa, Japan	Frontal reef crest	50 m^{-2}		Hohenegger, 1994
Marginopora sp.	Oahu, Hawaii	0–10 m	$0{\cdot}237 \times 10^4$ m^{-2}	6 g m^{-2} $year^{-1}$	Muller, 1976
M. vertebralis	Okinawa, Japan	Frontal reef moat	80 m^{-2}		Hohenegger, 1994
		Central reef moat	50 m^{-2}		
Archaias angulatus	Largo Sound, Florida	1 m	$0{\cdot}5 \times 10^4$ m^{-2} to 17×10^4 m^{-2}	60 g m^{-2} $year^{-1}$	Hallock *et al.*, 1986
Amphisorus hemprichii	Gulf of Aqaba, Israel	Seagrass meadow	150–350 per 225 cm^2 (leaf surface)	160 g m^{-2} $year^{-1}$	Reiss & Hottinger, 1984
	Chagos Archipelago	Lagoon	0–324 per 85 cm^2		Murray, 1994
	Okinawa, Japan	Frontal reef moat	290 m^{-2}		Hohenegger, 1994
		Central reef moat	160 m^{-2}		
Sorites orbiculus	Chagos Archipelago	27 m; lagoon	92 per 85 cm^2		Murray, 1994
Various rotaliines, including amphisteginids, calcarinids and nummulitids	Palau, W. Caroline Islands	Seaward reef flat		Max. 2800 g m^{-2} $year^{-1}$	Hallock, 1981
		Lagoonal reef slope		600 g m^{-2} $year^{-1}$	
		Seaward reef slope		150 g m^{-2} $year^{-1}$	
*Heterostegina depressa**	Oahu, Hawaii	0–10 m	$0{\cdot}311 \times 10^4$ m^{-2}	8 g m^{-2} $year^{-1}$	Muller, 1976
	Chagos Archipelago	Lagoon	<20 per 85 cm^2		Murray, 1994
	Okinawa, Japan	Reef flat	10 m^{-2}		Hohenegger, 1994
	West Pacific	25 m	Max. 46 per 500 g sediment		Hohenegger *et al.*, 2000
*Operculina ammonoides**	Chagos Archipelago	Lagoon	230–642 per 85 cm^2		Murray, 1994
	SW Sulawesi, Indonesia	12–33 m; reef base	Max. 3 per cm^2		Renema & Troelstra, 2001
	West Pacific	43 m	Max. 40 per 50 sediment		Hohenegger *et al.*, 2000
*Palaeonummulites venosus**	West Pacific	35 m	Max. 28 per 500 g sediment		
*Operculinella cumingii**		68 m	Max. 13 per 500 g sediment		
*Cycloclypeus carpenteri**		82 m	Max. 3·5 per 500 g sediment		
*Planoperculina heterosteginoides**		105 m	Max. 44 per 500 g sediment		

sea-level histories of the three facies associations presented above, also argues against a dominantly eustatic control on depositional sequences.

Despite the strong depth-dependent carbonate production rates, with *Nummulites* being produced in large numbers in very shallow waters, we conclude that ramp-like stratal geometries developed during deposition of the El Garia Fm as a consequence of strong offshore transport, combined with an absence of framework-building organisms. We contend that these conclusions about the location of the *Nummulites* 'factory' and sediment dispersal patterns appear to be broadly applicable to *Nummulites*-dominated platforms. However, conclusions drawn from the El Garia Fm may not be applicable to other nummulitic limestones on a much smaller scale. The El Garia Fm appears to reflect deposition in a unique palaeoecological situation on the southern margin of the Tethys Ocean, and differs dramatically in composition from many other circum-Tethyan nummulitic limestones. Despite having been deposited within the tropics (22°N; Dercourt *et al.*, 2000), the El Garia Fm contains a very sparse, typically warm-temperate biota, with only two common genera of larger foraminifera. The El Garia Fm also lacks key components of the photozoan association, e.g. aragonite, corals and calcareous green algae. Other Eocene nummulitic limestones commonly contain fully tropical biota (e.g. the early Eocene Jdeir Fm in Libya; Anketell & Mriheel, 2000). The sparse biota of the El Garia Fm indicates deposition under environmental conditions not typical of the Peri-Tethys. As noted by Schlager (2000), adverse environmental conditions may result in the substitution of the cool-water factory for the tropical factory in low latitudes. We speculate that during deposition, the El Garia Fm may have been affected by extremes of salinity, seasonally cool temperatures, fluctuating trophic resources, or perhaps, considering the fragmented state of many *Nummulites* tests, atypically high water-energy levels. Such differences need to be borne in mind when using the El Garia Fm as a direct analogue for other nummulitic limestones, and assessing just where it fits into the 'spectrum' of models for nummulitic limestones is perhaps an interesting area for future study.

CONCLUSIONS

This integrated outcrop, taphonomic, morphologic and biofabric study of *Nummulites* tests and populations, and the application of extant analogues, indicates that the highest rates of nummulitic sediment production occurred in the euphotic water that covered shallow-submerged palaeohighs, and also in nearshore environments, where fecund, short-lived, megalospheric (A-form) *Nummulites* thrived. *Nummulites* on the palaeohighs were transported in large quantities into the surrounding deeper water by turbidity flows and storm currents. Transport was facilitated by the windward orientation of the ramp, oceanic currents, and the lack of a sediment-trapping fringing reef. We conclude that the thin packages of El Garia Fm that crop out across the palaeohighs represent remnants of the large volumes of sediment that were produced on the highs and 'exported' into the surrounding deeper water, rather than being, as suggested by some authors, stratigraphically complete, condensed sections.

Transport of sediment from the palaeohighs resulted in abrasion and fragmentation of *Nummulites*, and produced a sediment package that gradually thickens and becomes increasingly fine-grained into mid and outer ramp environments. We conclude that down-ramp transport of *Nummulites*, combined with limited sediment production in deeper mesophotic and oligophotic environments by B-form and elongate A-form *Nummulites*, exerted a major control on development of the ramp-like geometries. Furthermore, bioturbation of mid and outer ramp sediments largely destroyed primary fabrics and stratification, strongly influencing facies development and stratigraphic architecture of much of the El Garia Fm.

Our model explains why earlier studies have generally been unable to identify widespread correlateable surfaces within the El Garia Fm, or define parasequences within these outcrops, or even identify third-order depositional sequences. Our findings bring into question models that use reef coral-derived sediment production and accumulation profiles to model accumulation of nummulitic limestones, or which claim to identify changes in accommodation space (reflected in variations in the size, shape and abundance of *Nummulites*) to the resolution of decimetre-scale Milankovitch cycles, even in largely allochthonous, thoroughly bioturbated, mid-ramp and outer ramp sediments which were deposited in a tectonically active basin.

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