A REVIEW OF EOCENE NUMMULITE ACCUMULATIONS: STRUCTURE, FORMATION AND RESERVOIR POTENTIAL

A. Racey*

Eocene nummulite accumulations, also referred to as nummulite "banks", form important hydrocarbon reservoirs in Tunisia and Libya and may constitute exploration targets in other parts of North Africa, the Mediterranean and the Middle East. Porosities commonly average 10-20% and permeabilities 10-50md. Foraminifera of the genus Nummulites may comprise up to 98% of the bioclasts in these carbonate reservoirs, although only one or two species may be present. The absence of associated fauna is generally taken to indicate an oligotrophic depositional environment.

In this paper, the palaeoecology of the genus Nummulites is discussed together with depositional models for two nummulitic carbonate reservoirs — the Middle Eocene Seeb Limestone of Oman and the Early Eocene El Garia/Jdeir Formation of Tunisia and Libya. The El Garia and Seeb Limestone Formations were deposited in ramp settings, and comprise a series of amalgamated sheets or low-relief banks. In the Hasdrubal field offshore Tunisia, where the El Garia Formation constitutes the reservoir rock, most of the nummulites have been redeposited from shallow into deeper waters whilst in the Bourri field (offshore Libya) they occur as an in situ "bank".

Nummulite accumulations often show evidence that both physical reworking (scouring, winnowing and imbrication) and biological processes (reproduction strategies and bioturbation) have influenced their formation. A general model is outlined for discriminating between physically and ecologically produced biofabrics, and the implications for reservoir quality are discussed.

INTRODUCTION

Nummulites are Tertiary (Late Palaeocene to mid-Oligocene) benthic rotalid foraminifera which are particularly common throughout the Tethyan region. Individuals are characterised by their large, generally lenticular tests which comprise a single planispirally-coiled layer subdivided into numerous simple chambers (Fig. 1). Nummulite accumulations or "banks" commonly occur in platform- or shelf-margin settings and mid- to outer ramp settings, particularly in the circum-Mediterranean region, the Middle East and the Indian Subcontinent

**BG Group, 100 Thames Valley Park Drive, Reading, Berkshire, RG6 1PT.*
email andrew.racey@bg-group.com

(Fig. 2). Eocene nummulitic limestones form important hydrocarbon reservoirs offshore Tunisia (Racey *et al.*, 2001) (e.g. *Ashtart* field: 350-400 MM brl) and Libya (Anketell and Mriheel, 2000) (e.g. *Bourri* field: 1,000-3,000 MM brl). They are potential exploration targets in Egypt, Italy, Oman and Pakistan.

The genus *Nummulites* has more nominal species (>300) than almost any other genus of foraminifera, but only a very small proportion of these species (<5%) are present in typical nummulite accumulations or "banks". These banks and /or the associated fore- and back-bank deposits are often rich in other nummulitids especially *Assilina* and *Operculina*. Most bank-forming species appear to be stratigraphically restricted to the uppermost Lower to Middle Eocene. Nummulite banks frequently have little associated micro- or macrofauna, suggesting that deposition took place in a nutrient-poor (oligotrophic) environment and/or in an environment with significant hydrodynamic sorting. Despite their commercial importance, the mode of formation and palaeoecology of these banks are still relatively poorly understood.

Two types of process — biological (mainly involving reproduction strategies) and physical (principally winnowing) — are thought to be responsible for the formation and fabric of nummulite banks. Post-depositional bioturbation and compaction may significantly modify the original fabric ("biofabric"). Physical processes are often identified as the principal mechanism of bank formation, and sedimentary structures indicating high-energy currents are common.

Although the term "bank" is often used to describe nummulite accumulations, it may not always be appropriate because an accumulation may not have had sufficient relief to significantly affect facies distribution. Accumulations can have variable depositional geometry, from being almost flat to strongly convex upwards. They vary in thickness from a few metres to hundreds of metres, and in lateral extent from hundred of metres to several kilometres.

Other genera of Tertiary shallow-marine foraminifera are also known to form banks — e.g. *Discocyclina*, *Assilina* and *Alveolina* in the Palaeogene, and *Lepidocyclina* in the Neogene — but these are less common and rarely reservoir significant volumes of hydrocarbons.

Previous work on Eocene Nummulites

Nummulite "banks" and depositional models, especially in Tunisia, Libya, Egypt, Italy and Oman, have been the subject of numerous studies over the last fifty years (e.g. Castany, 1951; Burrolet, 1956; Arni, 1965; Blondeau, 1972; Compte and Lehman, 1974; Fournié, 1975, 1978; Bishop, 1975, 1985; Arni and Laterno, 1976; Decrouez and Laterno, 1979; Aigner, 1982, 1983, 1985; Moody, 1987, Moody and Grant, 1989; Bailey *et al.*, 1989; Racey, 1988, 1995; Loucks *et al.*, 1998). Other investigators treated nummulite tests as transported sedimentary particles in slope and turbidite settings (e.g. Roniecwicz, 1969; Santisteban and Taberner, 1980; Wells, 1986).

Arni (1965) described "nummulite banks" as barriers separating "fore-bank" from more restricted "back-bank" environments, and assumed that the presence of a bank brought about a change in sea-bed morphology. This model was followed with little modification by numerous subsequent authors. Aigner (1983), in a study of Middle Eocene nummulite build-ups in Egypt, and Moody (1987), in a study of Early Eocene nummulite build-ups in Tunisia, identified shoals and shoal reefs as possible depositional environments (Fig. 3). Racey (1988, 1995) studied Middle Eocene nummulite accumulations in Oman, and identified a low-amplitude nummulite bank complex in a mid-ramp setting (*see below and Fig. 8*). Buxton and Pedley (1989) concluded that nummulite deposits in the Tethyan Tertiary were generally associated with ramps, and interpreted them to have been deposited in shallow-water, shoaling, inner ramp environments analogous to the coralgal patch reef belt (Fig. 4).

Arni (1965) and Arni and Laterno (1976) also noted that current and wave reworking were important controls on the formation of nummulite accumulations. Subsequent researchers such

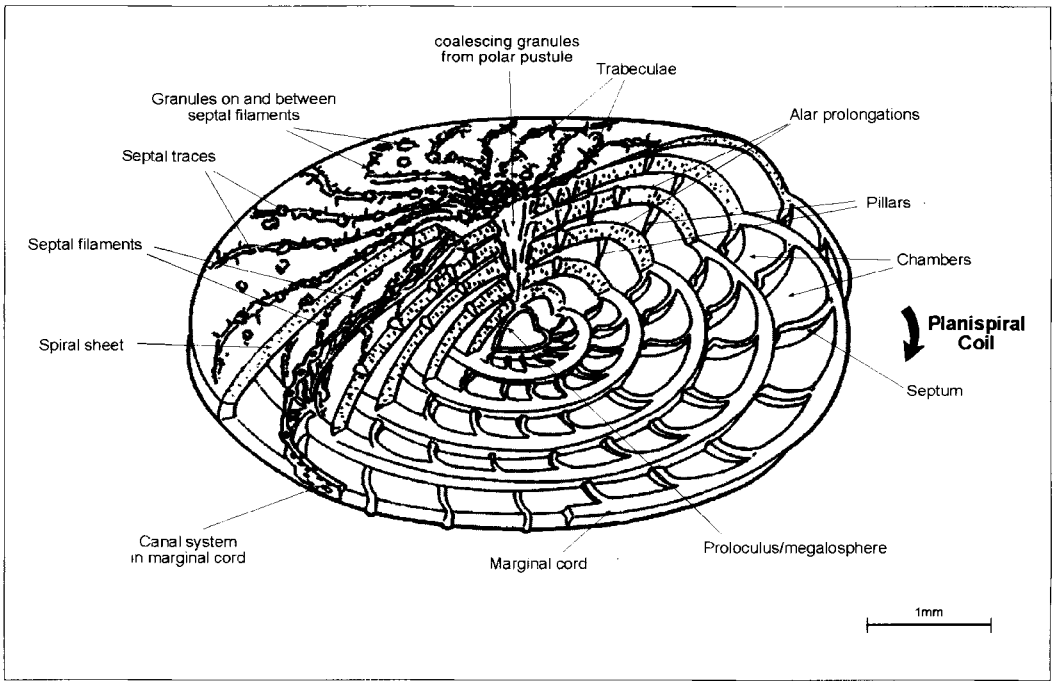
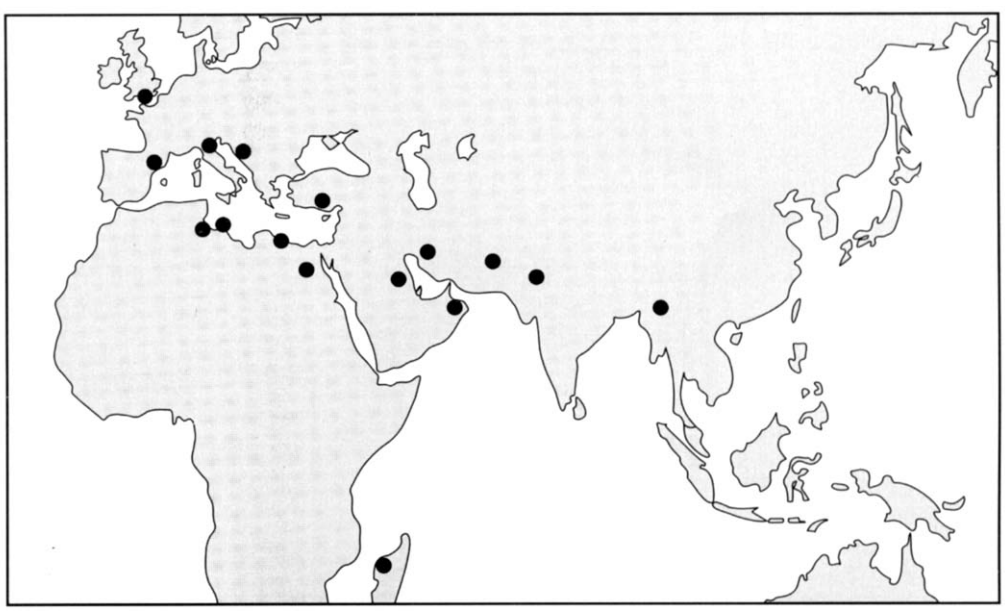


Fig. 1. A-form (megalospheric) nummulite morphology (after Racey, 1992).



● Significant Eocene nummulite accumulations in carbonates

Fig. 2. Geographic distribution of principal Eocene nummulite accumulations. Note the distinctive band of these facies around the margins of Tethys.

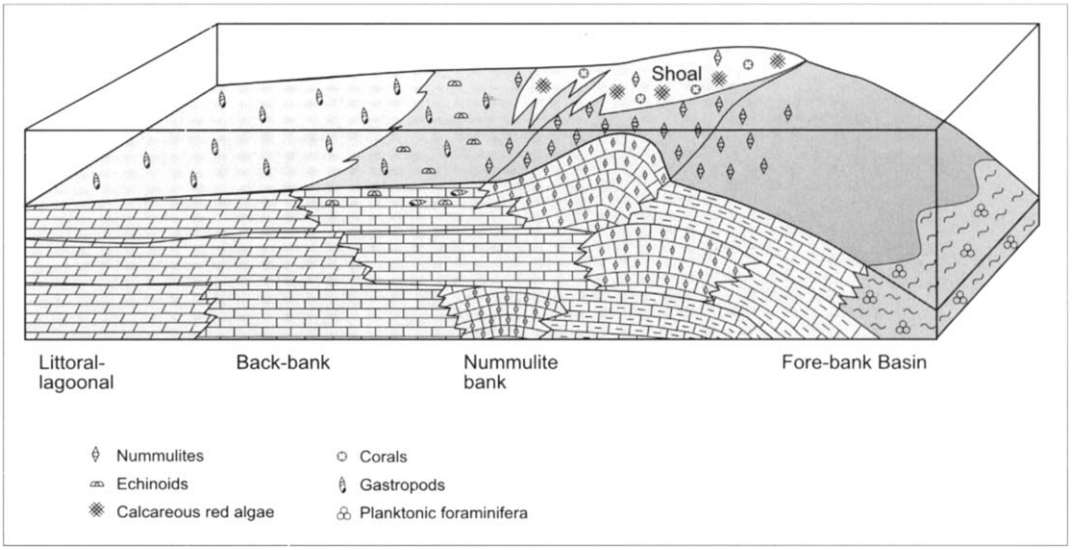


Fig. 3. Modified version of Arni's (1965) nummulite bank model used by Aigner (1983) to describe the Middle Eocene nummulite banks and associated facies of the Mokattam Formation, Egypt.

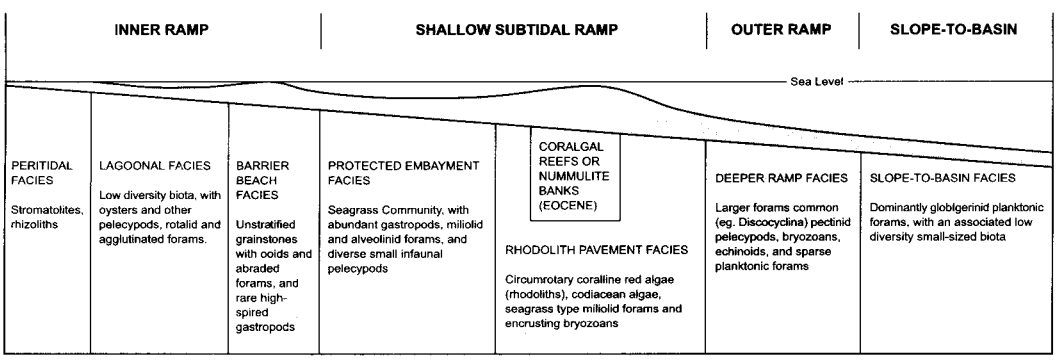


Fig. 4. Generalised Tertiary carbonate ramp model showing the main depositional environments and associated faunas (modified from Buxton and Pedley, 1989).

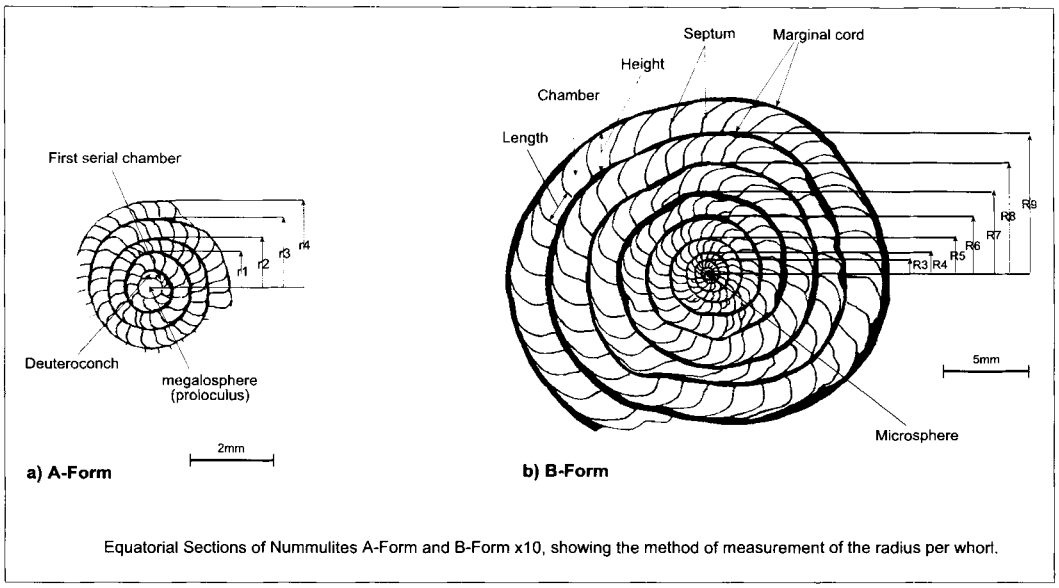


Fig. 5. Differences between *Nummulites* A-forms (megalospheric generation) and B-forms (microspheric generation). Numbers prefixed with r/R indicate the radius to successive whorls. A-forms are small, comprise relatively few whorls and have a large first chamber (hence "megalosphere"); while B-forms are large, have relatively many whorls and have a small first chamber (hence "microsphere").

as Fournié (1975) and Aigner (1983) suggested that nummulite banks formed on pre-existing structural highs.

From the literature it is difficult to formulate a general model for the distribution of nummulites since different authors tend to use different terminologies for describing such accumulations (reefs, banks, shoals) or else they emphasise different aspects of nummulites morphology(e.g. large versus small, megalospheric versus microspheric, or thick versus thin forms).

Personal Observations

It is my experience that nummulites occupied a broad range of environments in open marine platform, shelf and ramp settings though they are invariably absent in more restricted environments. Most of the examples I have seen in the field and in core possess a sheet-like or very low-amplitude bank-like geometry. In general large flat *Nummulites* tend to be associated with large flat *Assilina* and *Discocyclina* in "deeper" more outer platform/shelf/ramp settings (50-80m water depth) whilst small and medium sized lenticular *Nummulites* are more often associated with *Alveolina* and occur in shallower inner platform/shelf/ramp settings. "Banks" of more robust medium to large sized lenticular to globular shaped *Nummulites* tend to occupy a position intermediate between these two extremes.

NUMMULITE ACCUMULATION BIOFACIES

Nummulite accumulations consist predominantly of packstones to grainstones, almost entirely composed of complete and fragmented nummulite tests. Other skeletal grains present may include rare echinoid ossicles and spines, larger benthic foraminifera such as *Discocyclina*

and *Assilina*, smaller benthic foraminifera, calcareous red algae and molluscan debris. Most facies described as nummulite banks lack a rigid framework of calcareous algae, corals or bryozoans, and it is likely that many are not autochthonous. Nummulite accumulations cannot therefore be considered true "reefs" since they are not characterised by an organic framework (Braithwaite, 1973); nor can they be described as "shoals" which are formed purely by physical processes (Fournie, 1975).

Extant nummulitids especially *Heterostegina depressa* and various species of *Operculina* are morphologically similar to the extinct genus *Nummulites*, and consequently modern ecological data on these groups may be cautiously applied to understanding the palaeoecology of *Nummulites*.

Nummulites have alternating asexual and sexual generations, characterised respectively by small A-forms and larger B-forms (Fig. 5). In nummulite banks, B-forms are often dominant in high-energy crestal locations, while the smaller A-forms and large flat *Discocyclina* are dominant in the deeper-water flank areas. The distribution of these two morphotypes is in general controlled by the hydrodynamics of the depositional system, although the precise distribution and palaeoecology of nummulites around a bank is poorly understood. Some authors (Blondeau, 1972) have suggested that they lived in sea-grass meadows on the flanks of the banks, as do morphologically- similar larger foraminifera at the present day. Studies of extant larger foraminifera have shown that, after death, the tests can easily be transported because the decay of organic material produces gases which are trapped within the chamber system thus making them buoyant (Hallock, *pers. comm.*). Nummulite tests can be transported en masse by storm currents (Aigner, 1982, 1983, 1985), and accumulations may be further modified by winnowing and other sedimentological and biological processes. Biofabric analysis, in which the orientation, packing and sorting of nummulite tests is recorded, can be used to interpret the hydrodynamic and depositional environment of nummulite accumulations (Aigner, 1983; Moody, 1987; Wells, 1986; Racey, 1988, 1995)

ECOLOGICAL CONTROLS ON NUMMULITE ACCUMULATIONS

Nummulites, in common with many other larger foraminifera including extant nummulitids and alveolinids, are believed to have lived symbiotically with photosynthetic algae and are therefore thought to have been restricted to warm (25°C), clear, shallow (<120m) waters within the euphotic zone (Reiss and Hottinger, 1984). In the symbiotic relationship, the nummulite provided shelter for the algae while the algae produced oxygen and nutrients for the nummulite host as bi-products of photosynthesis. Light intensity and water energy are considered to be the two most important factors controlling the distribution of modern larger foraminifera.

Ecological processes, in particular reproduction strategies, are important in determining the fabric of nummulite accumulations. In common with most other larger foraminifera, *Nummulites* have a dimorphic life cycle comprising abundant, small (0.25-2.5cm diameter), asexually-produced A-forms which have a large first chamber or megalosphere; and less common, larger (0.5-10cm diameter), sexually-produced B-forms with a very small first chamber or microsphere (Fig. 5). Many authors have assumed that the asexual and sexual generations alternate, and give rise to an assemblage with an A- to B-form ratio of approximately 10:1 (Blondeau, 1972). Departures from this ratio have been used to define a "degree of winnowing" (Aigner, 1982, 1983 and 1985; Moody 1987). However, this must be treated with extreme caution since the actual ratio of A to B forms for fossil species is not known. It is relatively easy for non-specialists to confuse A-forms of one species with B-forms of another species, or to confuse juvenile B-forms with A-forms of the same species, particularly when observations are based wholly on hand specimens. These difficulties can lead to the calculation of incorrect A:B-form ratios.

In extant nummulitid foraminifera such as *Operculina* and *Heterostegina*, the ratio of A:B-forms in "life assemblages" may be extremely variable (see Reiss and Hottinger, 1984 and

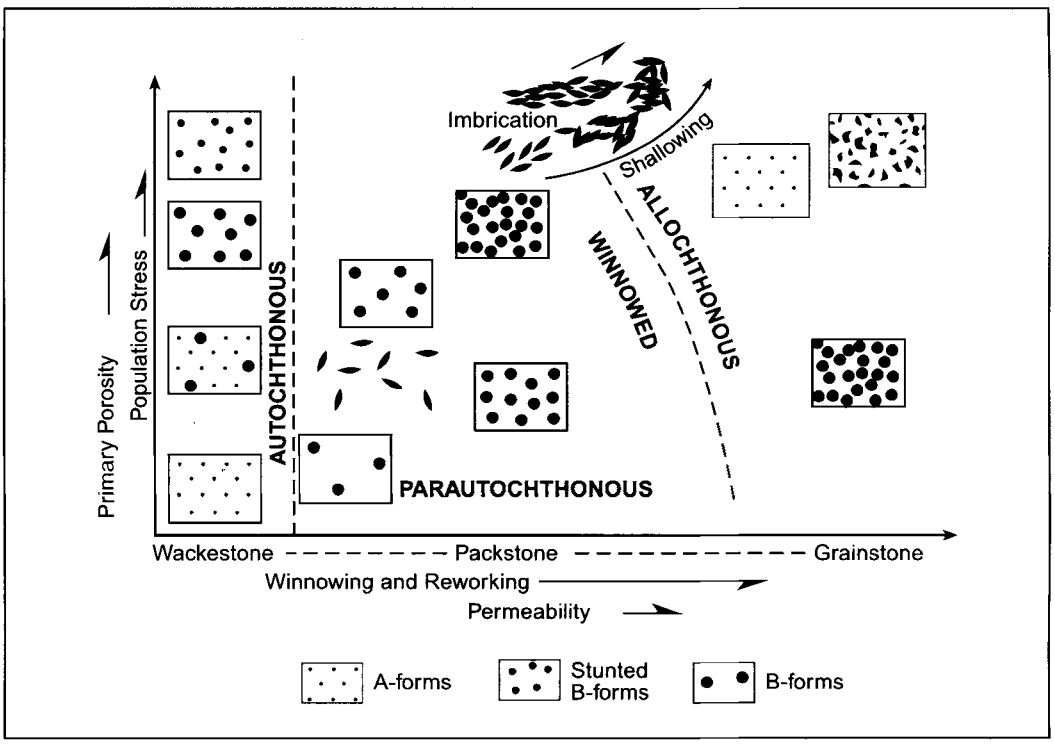


Fig. 6. Idealised model showing larger foraminiferal biofabrics and their possible relationship to reservoir quality. Three general types of fabric are defined: (i) autochthonous, i.e. in-situ fabric variations are due solely to environmental processes especially population stress (oligotrophy); (ii) para-autochthonous, in which the original biofabric is altered as a result of winnowing and the removal of matrix and smaller A-forms leaving the larger B-forms approximately in-situ; and (iii) allochthonous, where A- and B-forms have been transported and hydraulically separated and/or broken by physical processes. Winnowing and reworking will remove finer material and cause fracturing of tests, thus increasing porosity and permeability. With increasing population stress nummulite tests become more concentrated, causing an increase in relative porosity.

references therein). The use of such ratios can therefore only be used in a very general sense. Experiments with living foraminifera have demonstrated that asexually-produced A-forms arise preferentially when environmental conditions are optimal for growth (Reiss and Hottinger, 1984). Presumably this allows a species to multiply as rapidly as possible in order to fill a favourable niche; under these conditions asexual reproduction is advantageous. Conversely, when environmental conditions are harsh and nutrients are restricted, sexual reproduction leading to the production of B-forms is favoured. This produces fewer individuals, allowing the limited nutrient supply to last longer. Sexual reproduction also permits mixing within the gene pool.

In any one species, the smaller A-forms tend to have a significantly higher thickness-to-diameter ratio than the associated B-forms, while the B-forms have a much larger test diameter. The surface area to volume ratio is therefore greater in B-forms, especially in the case of bank-forming species which tend to be larger. A large surface area may be advantageous in oligotrophic conditions or in low light intensities, in that more symbiotic algae will be exposed to incident light near the surface of the test.

The occurrence of common smaller-than-normal B-forms has been taken to indicate extremely oligotrophic environments leading to stunting. However, it is also possible that

small B-forms represent individuals who reproduced early in response to favourable conditions and then died. Death follows reproduction in many extant larger foraminifera including the nummulitid *Heterostegina depressa* (Rottger, 1984).

Nummulites may have had a trimorphic life cycle with three generations (two A-forms and one B-form). This has been observed in *Heterostegina depressa* (Rottger, 1987). Trimorphism would be virtually impossible to detect in the fossil record. However, if present, it would radically affect determinations of A:B form ratios.

Distinctive depth-related larger foraminiferal assemblages, which are believed to reflect the type of algal symbiont present, have been recognised in Tethyan Palaeogene carbonate successions, and are commonly used for classification purposes (Henson, 1950; Buxton and Pedley, 1989; Racey, 1995). However, water depth is not the main control on the distribution of these taxa; environmental factors which vary with depth such as temperature, light intensity, water energy, turbidity and substrate type are more important. These environmental influences on assemblage composition are interdependent. Sediments rich in larger foraminifera are often inferred to represent deposition in oligotrophic settings, since such facies are often associated with organisms tolerant of nutrient-poor conditions such as corals and calcareous algae.

The following features indicate a biofabric which has not been disturbed significantly by winnowing and other physical processes:

1. Nummulite tests are rarely abraded.
2. A-forms are far more abundant than B-forms (a ratio of 10:1 has often been quoted, although this figure has never been substantiated by studies on living nummulitids).
3. Tests are encrusted on only one side by calcareous algae, bryozoa, serpulid worms or small oysters, indicating low current energies.
4. Nummulite abundance is independent of grain size, and all sizes are represented from small juveniles to large adults.
5. Borings such as bag-shaped *Trypanites* and various meandering to spiral annelid and sponge borings are relatively common suggesting limited winnowing/lateral transport.
6. Grainstones are rare while wackestones and packstones are dominant.

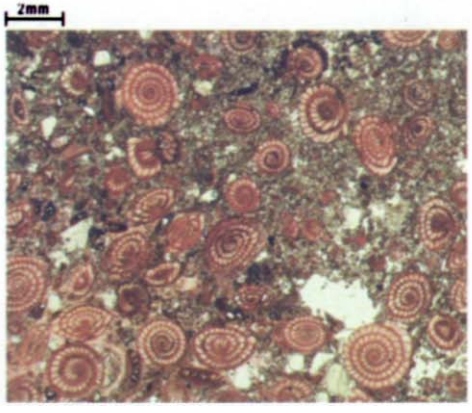
"Autochthonous" nummulite biofabrics, which principally reflect palaeoecological rather than physical conditions, are illustrated schematically in Fig. 6. Various biofabrics are illustrated in Plate 1; more detailed discussion were given by Aigner (1983, 1985) and Racey (1995).

PHYSICAL CONTROLS ON NUMMULITE ACCUMULATIONS

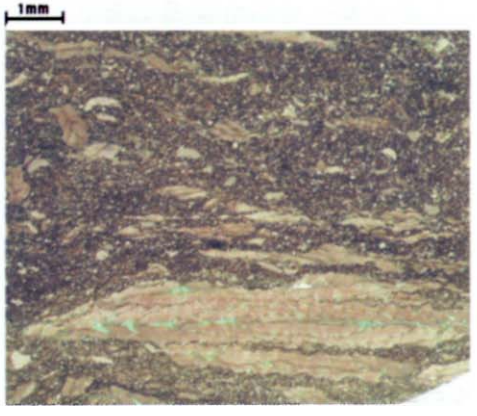
Physical properties of Nummulite tests

The hydrodynamic properties of nummulite tests have been deduced from flume tank studies (Futterer, 1982; Aigner, 1982; Racey, 1995). Inferred bulk densities range from 0.305 (living larger foraminifera) to 2.71 g/cu. cm (for pure calcite i.e. fossil forms). Pick-up velocities vary from 18 to 34 cm/sec for A-form nummulites with test diameters of 2-7mm; and 31 to 77 cm/sec for B-form *Nummulites* with test diameters of 20-35mm (velocities for unfossilised tests would probably have been lower since they would have been filled with air and organic material and would thus have been significantly lighter). Storm-induced wave current velocities of this order of magnitude have been recorded at depths of as much as 100m (Logan *et al.*, 1969). Settling velocities for *Nummulites* with test diameters of 7-24mm and thicknesses of 3.5mm were found to be equivalent to that of very coarse quartz sand (1-2.0 mm).

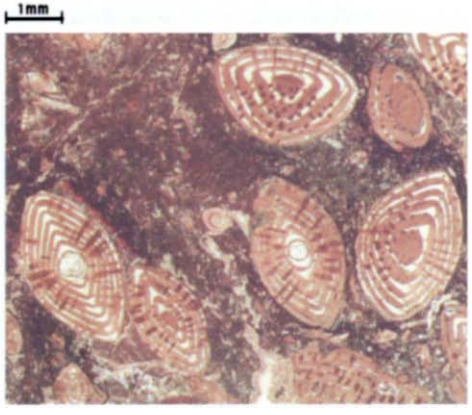
Porosity estimates for nummulite tests vary from 0-50% depending on the grain size and lithology of the surrounding sediment. Finer-grained material can enter the test via surface



Mixed autochthonous assemblage dominated by A-forms with rare fairly small B-forms (bottom right) in a partly recrystallised groundmass. Middle Eocene, Seeb Limestone Formation, Oman.

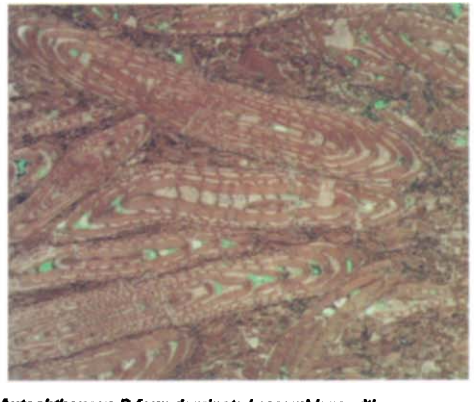


Allochthonous nummulociastic packstone-wackestone with strongly abraded B-form (bottom) which still retains some intraparticle porosity (green). Lower Eocene, El Garia Formation, Offshore Tunisia.

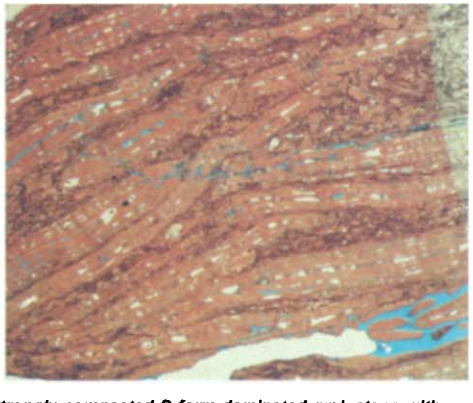


Autochthonous A-form dominated wackestone. Note minor boring of A-form to right of centre. Middle Eocene, Seeb Limestone Formation, Oman.

Mainly A-form dominated allochthonous grainstone with common nummulociastic debris. In core this interval is seen to be bioturbated. Lower Eocene, El Garia Formation, Offshore Tunisia.



Autochthonous B-form dominated assemblage with common nummulociastic debris. Note mainly intraparticle porosity (green). Lower Eocene, El Garia Formation, Offshore Tunisia.



Strongly compacted B-form dominated grainstone with common nummulociastic debris. Note some intraparticle and minor dissolution porosity (blue). Lower Eocene, El Garia Formation, Offshore Tunisia.

Plate 1. Selected nummulite biofabric textures from the Eocene of Tunisia and Oman. See also Plate 2 in Racey *et al.* 2001 (p. 35 of this issue).

pores and thus significantly reduce the intraparticle porosity. Porosity measurements on the extant larger foraminifera *Amphisorus* are as high as 72% (Aigner, 1985).

Calculations were attempted (BG Internal report) to determine the "shear" velocity or velocity needed to move nummulite particles from rest on the sea bed, and their average flow velocity using the methodology outlined by Hein (1982). A totally-cemented B-form nummulite test of diameter 3.5 cm is approximately equivalent to a 3.5-cm diameter quartz sand grain, since the respective bulk densities are very similar (2.65 gm/cm^3 for calcite and 2.71 gm/cm^3 for quartz). Such a test would have a shear velocity of about 18 cm/sec and a flow velocity of 2.8m/sec. The latter velocity is typical of a storm current, which could therefore move solid nummulite tests around a shelf margin with ease. A similar-sized nummulite with 40% porosity (common in Tunisian and Libyan accumulations) would have a shear velocity of approximately 7 cm/sec and a flow velocity of about 1 m/sec. The latter velocity would be typical of a strong tidal current, and would suggest that nummulite "bank" material could easily be moved in the outer shelf along the shelf margin, with concentrations occurring in intrashelf depressions or around sediment baffles. Storm currents of 2 m/sec could form washover tongues into back-bank areas.

Physical controls

Aigner (1985) considered that accumulations of nummulites are particularly suitable for hydrodynamic study, since their test shape is relatively simple and the size distribution of the original population can be assumed with some degree of confidence. However, as noted above, the ratio of A:B-forms (a ratio of 10:1 was used by Aigner), and to a certain extent test size in B-forms, can be affected by ecological factors and reproduction strategy.

Physical processes such as the winnowing of matrix material and of smaller A-forms are known to be important in the formation of nummulitic accumulations (see Arni, 1965; Aigner, 1982, 1985; Racey, 1995). These authors discussed evidence for the operation of physical processes, including size sorting, the packing and imbrication of tests (Fig. 7), and the occurrence of lag deposits and nummulitic "hash horizons". These sedimentary structures can be used to interpret the hydrodynamics and depositional environments of the accumulation.

The following features indicate a para-autochthonous to allochthonous biofabric which has been formed principally by physical processes:

1. The fabric is enriched in larger B-forms, and smaller A-forms and mud matrix has been removed by winnowing.
2. Nummulitic "hash horizons" and scattered broken nummulite tests are common.
3. Encrustation (and to a lesser extent boring) of nummulite tests is rare, suggesting continual movement by wave or other currents.
4. High-energy sedimentary structures (such as scours) and imbrication of nummulite tests (Fig. 7) are common.
5. Nummulite tests are often abraded.
6. Grainstone and packstone fabrics dominate.

Dominantly "parautochthonous" to "allochthonous" nummulite biofabrics which reflect significant physical transport and winnowing are illustrated schematically in Fig. 6. Plate 1 illustrates various representative biofabrics; further details were given by Racey (1995).

PROBLEMS WITH BIOFABRIC INTERPRETATION

Fig. 6 illustrates the range of biofabrics recognised in larger foraminiferal accumulations, and shows that higher permeabilty allochthonous fabrics can clearly be differentiated from autochthonous fabrics. However, as noted above, there are a number of problems associated

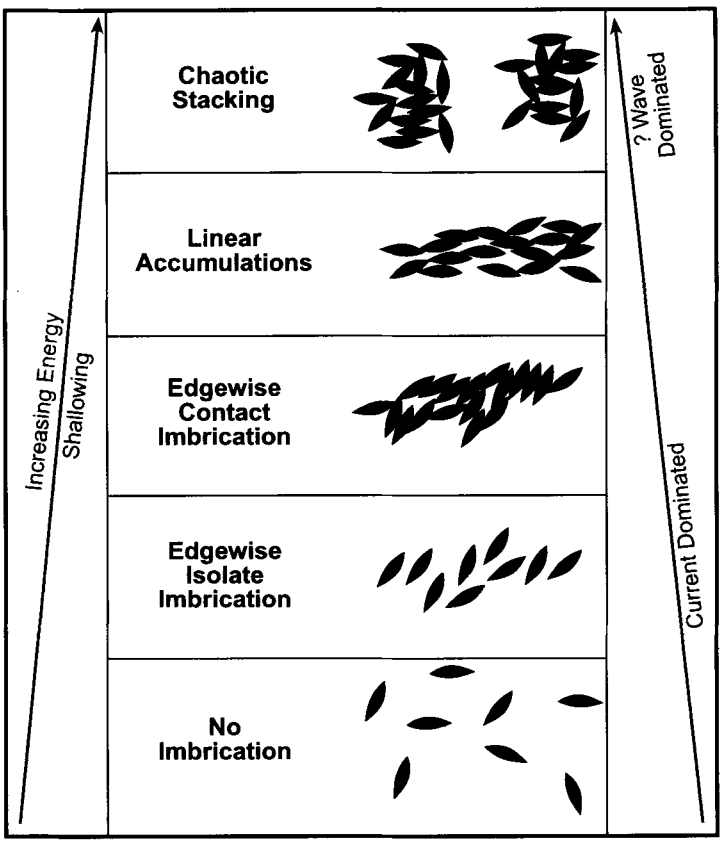


Fig. 7. Imbrication styles in nummulite accumulations. Style of imbrication changes with increasing hydraulic energy -- shallowing causing a progressive concentration of nummulite tests as current energies increases. Ultimately, wave influences become dominant and obvious imbrication gives way to a chaotic stacking of tests.

with biofabric interpretation. For example, empty tests do not necessarily indicate the death of an individual, but probably reflect abandonment during reproduction. Also, A:B-form ratios are not known with certainty for fossil nummulites and are poorly-known for living nummulitids. Moreover, seasonal changes in A:B form ratios may have occurred, but would not be discernible in the fossil record. Thirdly, smaller-than-normal B-forms could represent both stunting due to unfavourable environmental conditions, and reproduction at a young age in response to favourable environmental conditions. B-form dominated assemblages may represent growth in less favourable environments where sexual reproduction was advantageous; A-form dominated assemblages may indicate highly favourable conditions. Fourthly, trimorphism, which has been observed in the living nummulitid *Heterostegina depressa*, may have occurred in extinct species, but would be almost impossible to discern in the fossil record. Finally, different species of *Nummulites* may have had different species of associated symbiotic algae which may have preferred different wavelengths of incident light, exerting an important control on the water depth occupied within the photic zone.

In addition to these controls, the effects of bioturbation and compaction on biofabric must also be considered. Bioturbation may significantly modify the original depositional biofabric,

yet may be difficult to identify and quantify due to a general lack of matrix grain size variation. Moreover, such nummulitic packstones and grainstones would constitute poor substrates for colonisation due to their large clast size and possibly also due to the high grain mobility. Compaction may cause alignment/imbrication of nummulite tests without recourse to wave or current action. Bioturbation may also lead to the development of discrete "patches" of imbricated tests which actually represent burrow linings rather than imbrication formed by physical processes. To further complicate matters, bioturbation can also modify pre-existing wave- or current-produced imbrication. The identification and quantification of these factors in cores where only a small portion of the nummulitic interval is visible may be problematic.

EXAMPLES OF NUMMULITE ACCUMULATIONS: OMAN AND NORTH AFRICA

Examples of nummulite accumulations are described below with special reference to Oman, Tunisia, Egypt and Libya. Many of these accumulations show evidence of significant physical reworking, although ecological controls on their formation are also important. Nummulite accumulations in other parts of the World, for which little information is available, are described briefly. Many of these nummulite banks accumulated on palaeotopographic highs of variable relief. The highs appear to have been optimal locations in terms of biological productivity, but because the overlying waters were shallow, physical processes especially winnowing occurred and modified the accumulations' biofabric.

Oman : the Seeb Limestone (Fig. 8)

A 500-m thick, storm-swept Middle Eocene carbonate ramp sequence is present in Oman and is assigned to the Seeb Limestone Formation. Nummulite biofabrics and sedimentary structures in the formation were discussed by Racey (1995) who proposed a general depositional model (the following resumé is based on this reference).

Although the nummulite fauna is diverse with over twenty species present, only two large species — *N. ex.gr. perforatus* and *N. ex. gr. gizehensis* — dominate the nummulitic part of the formation, which has a total thickness of about 200m. Calcareous green algae occur in the lower part and red algae in the upper part of the Seeb Formation, while corals and other macrofossils (especially molluscs and echinoids) are rare but occur sporadically throughout.

Larger foraminifera can be divided into a succession of depth-controlled microfacies which are, from shallowest to deepest (Fig. 8): miliolids and textulariids (Facies A); *Somalina* (Facies B); *Alveolina* (Facies C); *Nummulites* (Facies D/E); *Assilina* (Facies F) and *Discocyclina* (Facies G). Planktonic foraminifera are absent even in the deepest *Discocyclina* facies, suggesting low productivity and nutrient supply. *Operculina* occurs sporadically throughout the *Assilina* and *Discocyclina* facies, while smaller rotaliids including *Lockhartia* are locally relatively common in the *Alveolina* and *Nummulites* facies. A shallower "back-bank" facies dominated by porcelaneous-walled foraminifera (miliolids and alveolinids) and calcareous green algae is separated by the nummulitic facies from a deeper "fore-bank" facies, dominated by perforate-walled foraminifera (assilinids, discocyclinids and operculinids) and calcareous red algae.

The nummulites generally occur in packstones-grainstones which form distinctive low-amplitude banks (1- to 10-m thick, thinning to a few centimetres towards the flanks), which are 100-200m long. These are often B-form dominated and show evidence of physical processes (scouring, test abrasion, imbrication and winnowing). The topographic relief on these nummulite banks was low; frequently, the banks take the form of a series of amalgamated nummulitic sheets which are slightly convex upwards. Within the nummulite "bank" facies, test borings *(Trypanites)* and encrustation by oysters are rarely observed, whilst *Thalassinoides*-type burrows are occassionally recorded. *Alveolina* in shallower waters and *Assilina* in deeper waters form

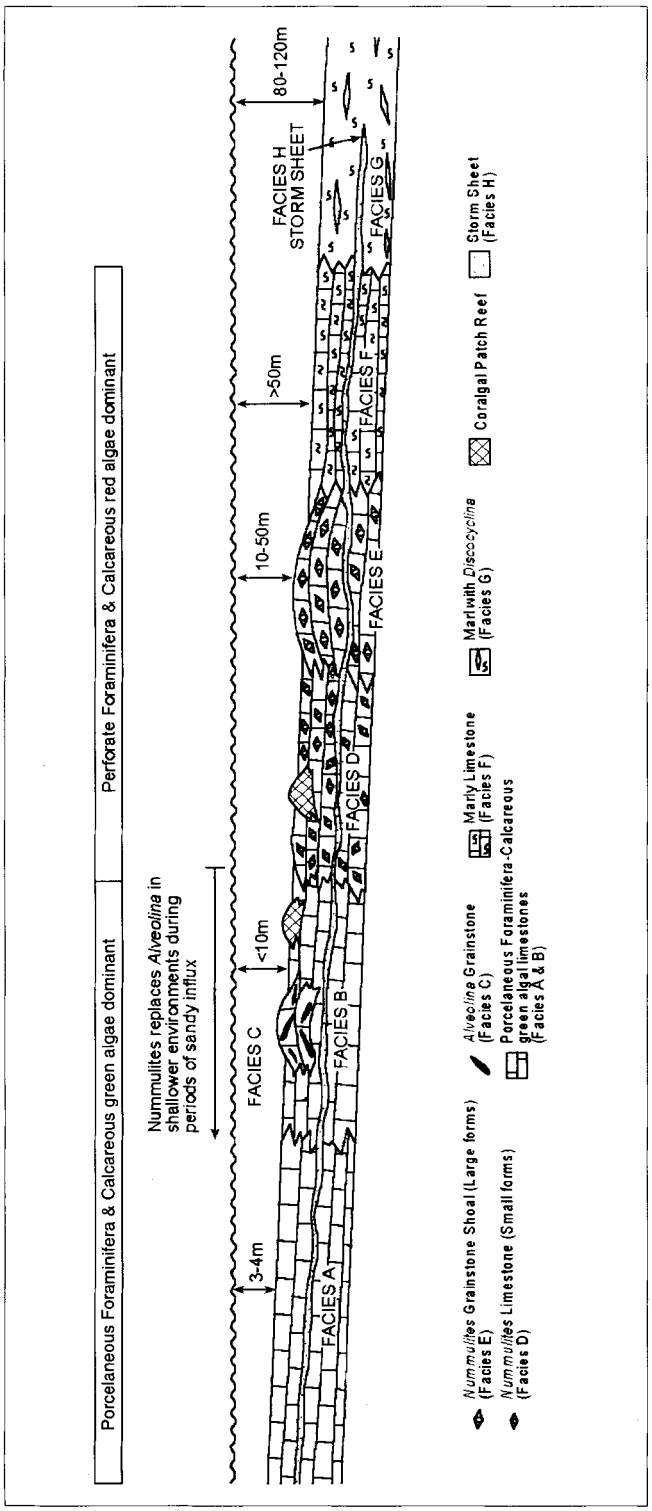


Fig. 8. Depositional model for the Middle Eocene Seeb Formation of Northern Oman showing generalized depth-controlled distribution of the main larger foraminiferal groups (*Alveolina*, *Nummulites*, *Assilina* and *Discocyclina*), and the location of the main nummulite accumulations in a mid-ramp setting.

generally similar, but significantly smaller, low- amplitude bank complexes. Storm sheets (graded and cross-bedded calcarenites with erosive bases) containing shallower-water microfossils (including calcareous green algae and miliolids) occur in successively deeper-water ramp settings. These storms may have produced the high energy currents necessary to produce the banks.

The lower part of the nummulite banks are dominated by A-forms, while erosional bedding contacts and B-form "lags" are more common in the upper parts. Imbrication (mainly of B-forms) changes from isolate to contact edgewise to chaotic stacking in the upper parts of the banks, suggesting an increase in energy due to shallowing and a change from current- to wave-dominated processes (Fig. 7). Large-scale planar bedding and intraformational truncation surfaces are more common in the upper (shallower) parts. Storm sheets containing a shallower-water microfauna occur throughout the formation, indicating that storm processes were important in the formation of the banks. Physical modification of the original nummulite assemblage and substrate by winnowing indicates that the banks are para-autochthonous. Porosity and permeability, which are generally affected by limited diagenesis, range from 0.7-14.5% and 8-95md, respectively.

North Africa

1. Tunisia

Shallow-marine and lagoonal carbonates of the Early Eocene (Ypresian) Metlaoui Carbonate Group, which includes the nummulitic limestones of the El Garia Formation (Fig. 9), occur along the north coast of Tunisia. They were deposited as a series of approximately shoreline-parallel facies belts on a broad, shore-attached NE-facing carbonate ramp (Racey *et al.*, 2001) (Fig.10). However, these facies were significantly modified by syndepositional faulting leading to the development of a complex pattern of facies controlled by palaeotopography. Nummulite banks (El Garia Formation) appear to have developed on local highs when palaeoenvironmental conditions were suitable, while organic-rich pelagic carbonates (Bou Dabbous Formation) accumulated in the adjacent lows and on the outer margins of the ramp. Between these two facies, aprons of redeposited nummulitic material (Ousselat Formation) accumulated either through storms or fault-induced sediment slumping. Lagoonal limestones and dolomites (Ain Merhotta/Faid Formation) were deposited on exposed and very shallow highs at this time.

Nummulite "banks" in the El Garia Formation onshore Tunisia have been studied by Compte and Lehman (1974); Fournié (1975); Moody (1987); and Loucks *et al.* (1998). The banks generally comprise nummulitic mud-poor packstones and poorly-sorted grainstones, deposited in shelf or mid-ramp settings, between fair-weather and storm wave base in water depths of 30-60m. Many of the sedimentary structures formed by wave and storm currents were subsequently destroyed or significantly modified by bioturbation (Loucks *et al.*, 1998; Racey *et al.*, 2001), and abrupt lateral and vertical changes in both rock texture and the ratio of A:B forms has been observed.

Hasdrubal field

For details of this field including representative photomicrographs and core photographs, see Racey *et al.* (2001); diagenesis and reservoir quality are addressed by MacCaulay *et al.* (2001).

The Eocene El Garia Formation in the *Hasdrubal* field (Fig. 9) is up to 90-m thick and was deposited in a mid-ramp setting. Porosity averages 10.5% (range 0.5-23%) and permeability averages 0.5 md (range 0.02-60 md). The El Garia is composed almost entirely of transported nummulites (98% of the bioclasts, represented by two species) with rare *Discocyclina*. The Discocyclinids are large and have thin unbroken tests, and are therefore assumed to have undergone only minimal post-mortem transport. The nummulitic facies have a predominantly

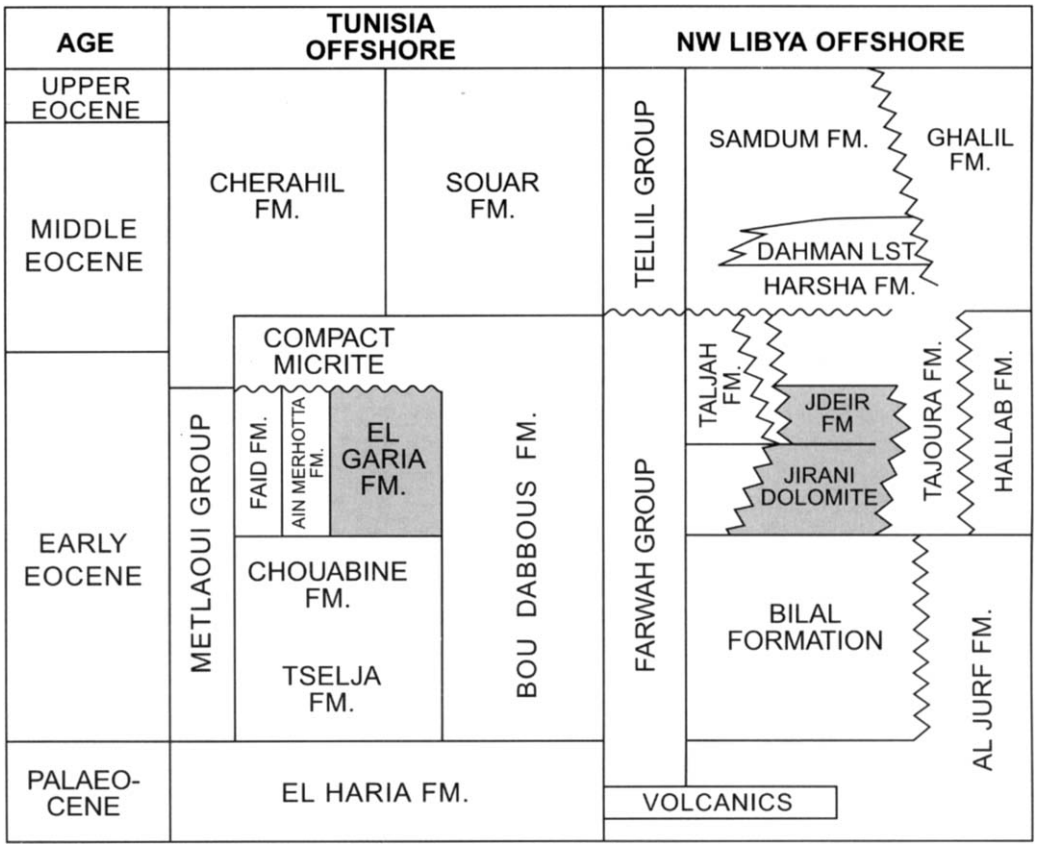


Fig. 9. Lithostratigraphic correlation for offshore Tunisia and offshore Libya, showing the approximate relative positions of the nummulitic reservoirs of the El Garia Formation (Tunisia) and the Jdeir Formation (Libya).

sheet-like geometry and show very little relief. Macrofossils such as echinoids and molluscs (oysters and low-spired gastropods) are very rare. Up-dip high energy nummulite shoals pass laterally into inner ramp lagoonal carbonates (Ain Merhotta Formation) and then into sabkha deposits (Faid Formation). Down-dip, the El Garia Formation passes into outer ramp basinal mudstones of the Bou Dabbous Formation.

Planktonic foraminifera are generally rare throughout the El Garia Formation and in the laterally equivalent basinal sequence (the Bou Dabbous Formation). Low plankton productivity suggests minimal upwelling, isolation and/or restriction from oceanic circulation. The dominance of nummulites which were capable of obtaining much of their energy and nutrient requirements via their algal symbionts suggests that the environment of deposition was nutrient poor i.e. oligotrophic.

The absence of encrusting organisms tolerant of oligotrophic conditions, such as corals and calcareous algae, suggests either that current energies were sufficiently high to have inhibited attachment and growth, or that sediment deposition rates were too great to permit colonisation. Alternatively, oligotrophy may have been extreme and only nummulites may have been able to tolerate these conditions.

Sedimentary structures including imbrication, graded bedding and the presence of nummulite "hash horizons" in packstones and grainstones suggests that the depositional setting was affected by high current energies. The nummulites are interpreted to have been redeposited into deeper waters either by storm or turbidity currents, and were subsequently partly bioturbated. Interbedded wackestones have yielded rare well-preserved planktonic foraminifera and large flat *Discocyclina*, supporting a deep-water depositional model. Cores from the El Garia Formation at *Hasdrubal* field show significant bioturbation by a relatively large unidentified organism (possibly *Thalassinoides* or echinoids) which has often significantly modified the original nummulite biofabric. Nummulitic packstones and grainstones would have formed poor, unstable substrates for colonization, while the patchy distribution of bioturbation suggests limited periods of opportunistic colonisation during fair-weather periods between storms.

Ashtart field

The largest field in the El Garia "trend" offshore Tunisia is *Ashtart* (Anz and Ellouz, 1985; Fletcher, 1985; Hmidi and Sadras, 1991: the following discussion is based on these references). Ashtart comprises a NW-SE trending asymmetric anticline about 10km long and 4.5km wide, and represents a combined stratigraphic/structural trap developed on a NE-prograding nummulite shoal. The reservoir pinches out into non-reservoir slope and basin facies (Bou Dabbous Formation) to the north, NE and SE and is structurally closed to the SW.

The El Garia reservoir at *Ashtart* is composed of nummulite packstones with subordinate wackestones and grainstones deposited in a high-energy bank/shoal The nummulites commonly show imbrication, cross-bedding and bioturbation. Primary intergranular porosity is markedly occluded by fringing and blocky calcite cements, while intraskeletal porosity within nummulite tests is often preserved but is ineffective. Reservoir quality was enhanced by leaching and by much later solution enhancement post-dating fracture and stylolite formation. Cores are moderately to highly fractured and late dolomite (<10% of rock volume) is present, especially in intervals with low permeabilities.

Average effective porosity over the cored interval is 17.2% with an average permeability of 50md (range 0.2 to 1000 md). Analysis of areal pressure gradients during water injection suggests that the reservoir does not behave like a highly communicating fracture system despite the presence of numerous fractures and faults observed in cores and on seismic profiles.

Porosities are generally high, due mainly to the large amount of ineffective (i.e. unconnected) intraparticle porosity present within the nummulite tests. Permeabilities are variable and often fairly low. The porosity of the El Garia Formation (on- and offshore) ranges from 1 to 35% (average 15%), and the permeability from 0.01 to 3,400md (average 6md).

Nummulitic limestones also occur in the younger Middle-Late Eocene Reineche Member (Cherahil Formation) which reservoirs gas condensates at the *Chergui* field on Kerkennah Island, and oil in the onshore *Cercina* field. Bioclasts are dominated by the nummulites *N. gizehensis* and less common *N. bullatus*. Bioturbation by *Thalassinoides* and by burrowing echinoids is common and is probably responsible for generating a significant amount of nummulithoclastic. It also has a marked influence on subsequent diagenesis and reservoir quality (Hauptman, *pers. comm.*).

2. Libya (after El Ghoul, 1991; Bernasconi *et al.*, 1991; Anketell and Mhriheel, 2000)

Nummulite banks with obvious depositional relief and of broadly similar ages have been recorded offshore NW Libya. The hydrocarbon play here is believed to be similar to that observed in Tunisia: an El Garia equivalent, the Jdeir Formation (Fig. 9), is the reservoir, and is sourced by a Bou Dabbous equivalent and sealed by the Souar Formation. However, the overall setting in Libya is different in that the Jdeir Formation occurs as a rimmed shelf with

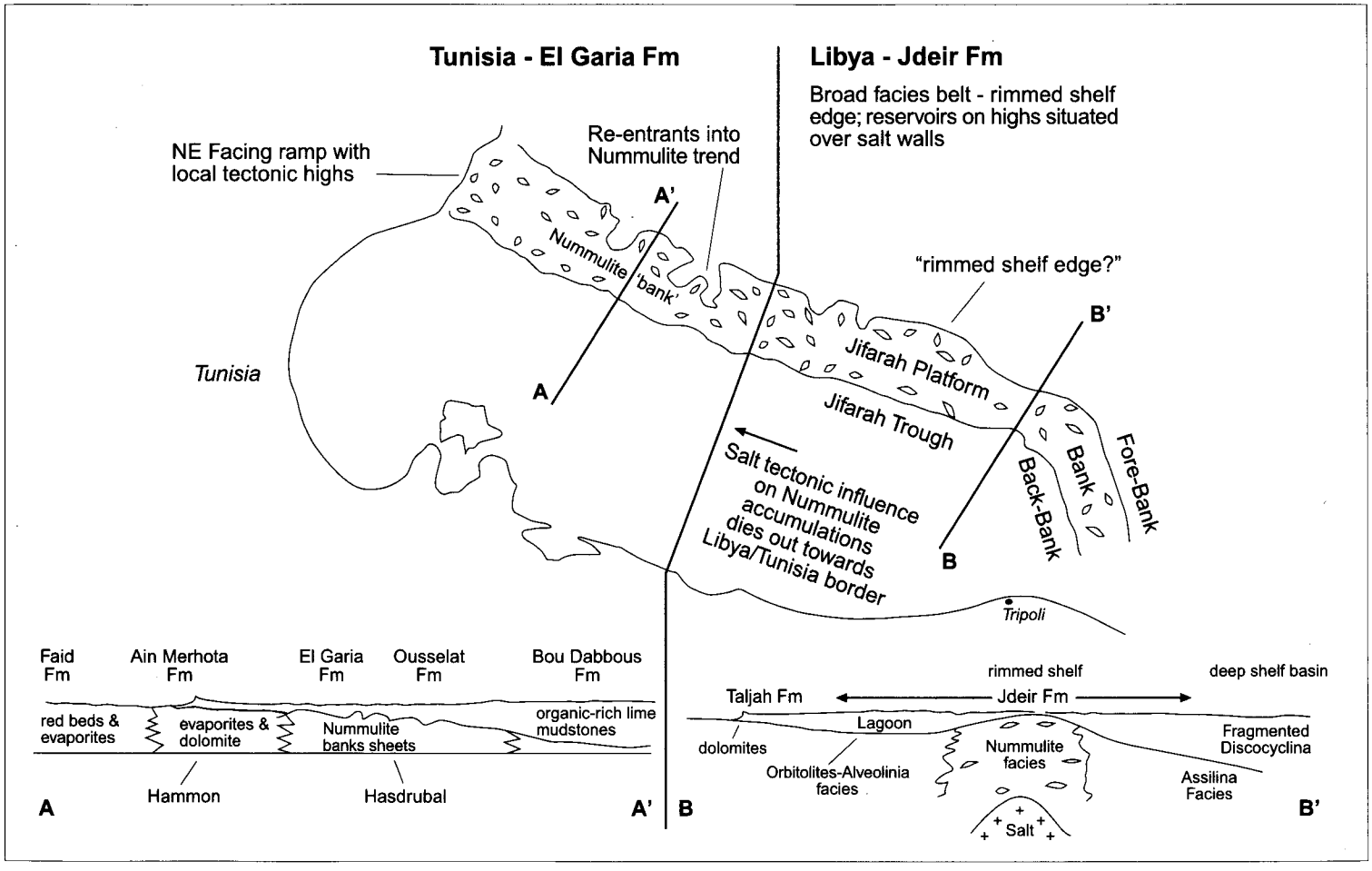


Fig. 10. Comparison of depositional settings for the Eocene nummulite accumulations in the El Garia Formation (Tunisia) and the Jdeir Formation (Libya).

the nummulitic Jdeir located over salt walls. Syndepositional movements of these salt walls allowed thick banks of nummulites to accumulate above them.

The giant *Bourri* oilfield, offshore NW Libya , comprises a reservoir couplet of a nummulitic Jdeir Formation together with the underlying Jirani Dolomite Member. Three nummulite bank complexes were recognised in the Jdeir Formation by Bernasconi *et al.*(1991).The field comprises an east-west trending anticline and is a combined stratigraphic/structural trap. The structure is believed to have been active during the deposition of the Jdeir Formation in the Ypresian due to deeper salt tectonism. Regional uplift along the Jifarah Arch at the end of the Ypresian caused significant erosion at the top of the Jdeir Formation in wells to the SE of Bourri where the Jdier Formation is absent. Bernasconi *et al.* (1991) noted that the deposition of nummulite bank facies was prevalent along the crest of the structure, and that the complex interaction of sedimentation rates, subsidence rates, eustatic changes and wave action produced lateral migration, reworking and "shallowing" of the nummulite banks. They considered periods of regression to favour the areal development of nummulite banks and, in this respect, noted that the uppermost nummulite bank is laterally the most extensive reflecting the more major regression at the end of the Ypresian. Meteoric leaching has significantly enhanced reservoir quality in the Jdeir Formation compared to the Tunisian El Garia Formation where this type of leaching is less common.

The Jdeir Formation has an average porosity of 16% (maximum 21%). However, reservoir quality varies significantly within the various nummulite bank facies from an average of 5% to 18%. The Jirani Dolomite mainly comprises restricted shallow platform and tidal flat sediments which are dolomitised and possess excellent mouldic and vuggy porosity. The average porosity is about 22% (range 16.7-27.1%).

Within the Sirte Basin to the SE, Arni (1965) recorded a vertical transition (shallowing) from nummulite dominated banks into shallower peneroplid-dominated shoal deposits.

3. Egypt (after Aigner, 1982 and 1983)

In the Middle Eocene succession of Egypt, true "banks" of nummulites dominated by *N. gizehensis* clearly affected deposition of surrounding facies. There is evidence in these banks for physical processes and winnowing. Moreover, macrofossils such as burrowing echinoids and molluscs (oysters and gastropods) are rare, suggesting that nutrient supply was not as critical a factor as inferred in the Tunisian and Oman examples above. Some of the nummulites are encrusted by small oysters, serpulids and bryozoans and are occassionally bored by *Trypanites*. Bed contacts within the nummulite banks often exhibit grainstones resting on wackestones and are often erosional and occassionally burrowed by *Thalassinoides* (*Spongiliomorpha* of Aigner). Erosive pockets filled with nummulite grainstone have been recorded, and are thought to reflect intense scouring by high energy currents (? storms), with several such layers often visible within a single bed suggesting amalgamation of multiple erosional and depositional events. These composite beds are especially common towards the top of the bank sequence. Larger nummulite B-forms are observed to be locally imbricated oblique to bedding.

A near back-bank shoal-reef facies, comprising patches of coral in a wackestone-packstone matrix containing nummulites, disarticulated oysters and various other bioclasts, overlies and interfingers with the nummulite bank facies (Fig. 3). This shoal-reef facies interfingers with, and is overlain by, a shoal facies (back-bank) comprising moderately-sorted skeletal packstones-grainstones containing nummulites, abundant miliolids, a rich and diverse mollusc fauna, echinoids, bryozoa, corals and coralline red algae. A low-energy back-bank facies (lagoonal) consists of mudstones and wackestones interbedded with thin marls. The bases of the limestones are often erosive and burrowed. Thin packstone horizons rich in nummulite A-forms are occasionally present and may represent higher energy (?storm) events. *Operculina* is fairly common and macrofossils are diverse and dominated by burrowing echinoids, serpulids,

Kuphus, oysters and bivalves plus rare corals and regular echinoids. The presence of *Operculina* may indicate deeper waters. Aigner suggested that while the nummulites accumulated on a topographic high frequently struck by storm events, these events were less effective in the deeper and more protected back-bank environment. The dominance of burrowing echinoids and bivalves suggests a muddy substrate in an open lagoon behind a barrier which was formed by a nummulite bank/shoal complex.

Philobbas and Keheila (1979) studied the Middle Eocene nummulite banks at Minia, southern Egypt, and recorded corallinacean-nummulite boundstones, one of the few examples of true nummulite dominated "reefs". They did not present data concerning reservoir quality, although photomicrographs provided indicated that most porosity is occluded by calcite cement and carbonate mud.

Other areas

Italy

Eocene (dominantly Lutetian) nummulite banks are present at Verona, northern Italy (Arni and Lanterno, 1972), together with an association of coralline red algae (*Lithothamnion)* which encrust most of the bioclasts, and common-to-abundant *Discocyclina* (mainly large, flat forms). This fauna may indicate a low energy platform/shelf setting. The presence of common *Discocyclina* may indicate moderate water depths within the photic zone. Locally, coralline red algae are the dominant bioclast.

Nummulite species are dominated by *N. gizehensis* with rarer *N. perforatus, N. millecaput, N. crassus* and *N. lyelli.* The nummulite banks are of fairly low amplitude, (25-40m) thick, with a crude wedge–shaped geometry which thins to zero from the crest of the bank complex over a horizontal distance of a few hundred metres. The banks appear to comprise a series of amalgamated sheets within which a number of erosive and condensed horizons were identified (Arni and Lanterno, 1972). These authors concluded that the banks formed a narrow zone towards the margin of a platform, and separated open-marine conditions from lower-energy back-bank conditions. The banks are thin, and Arni and Lanterno therefore suggested that waves were able to transport bioclasts associated with the nummulite bank into the back-bank setting. No data was presented concerning reservoir quality.

Former Yugoslavia

Early Eocene *Nummulites-* (and *Alveolina-*) rich limestones have been reported near Split (Croatia) and include "reefal banks of *Nummulites*" (Chorowicz, 1975). Similar nummulite banks were reported by Bignot (1972) and Cadet (1976) from Istria, where they pass laterally into *Alveolina* then lagoonal miliolid-rich limestones. Eight facies were identified, from shallowest to deepest:

1. lagoonal to lacustrine limestones with discorbid foraminifera, charophytes and gastropods;
2. lagoonal limestones with *Spirolina* and miliolid foraminifera;
3. limstones rich in porcellaneous foraminifera, particularly *Alveolina* and *Orbitolites* ("back-bank");
4. detrital limestones with molluscs and a diverse foraminiferal assemblage (near "back-bank" shoal);
5. biohermal nummulite limestones (nummulite bank);
6. argillaceous limestones with large, flat common rotalid foraminifera especially *Nummulites, Assilina, Operculina* and *Discocyclina* (proximal fore-bank);
7. marls with *Operculina* and *Discocyclina* (distal fore-bank);
8. shales with planktonic foraminifera, interbedded with flysch containing redeposited larger foraminifera (deep marine).

RESERVOIR MODELS

In the Seeb Limestone Formation of Northern Oman, there is a relationship between the depositional fabric of the nummulite accumulation and its reservoir quality (Racey, 1995). Compaction and diagenesis are relatively insignificant, as is fracturing. By contrast, in the El Garia Formation of Tunisia, although similar biofabrics are discernible there is not such a clear relationship between fabric and reservoir quality. However, in the *Hasdrubal* field, extensive (but commonly localised) diagenesis (especially dolomitisation) and significant compaction leading to the formation of stylolites (especially at bed boundaries) has modified the original biofabric. In fact, one of the main controls on reservoir quality in the El Garia Formation is dolomitisation (and in some cases dedolomitisation), which does not appear to be fabric selective. Bioturbation has also modified the original depositional fabric locally at *Hasdrubal*.

Better quality reservoirs are generally developed where there has been little initial compaction, where nummulithoclastic debris and lime mud are absent, where the nummulite tests have been moderately to well sorted, and where there has been minimal precipitation of late burial cements. Consequently, primary depositional fabric can be correlated with reservoir quality, although later diagenetic processes may obscure or obliterate this trend. Many nummulite accumulations have high porosities, but much of this porosity is intraparticle (i.e. confined within the chambers of the nummulites) and is ineffective, being associated with relatively low permeabilities. Winnowing of the finer matrix and/or diagenesis are often required to improve permeability and in some cases to enhance porosity. Matrix-free grainstones have the greatest potential to produce a permeable interparticle pore-network during diagensis, although this can be destroyed by early compaction. However, if too much matrix is present between the nummulite grains then the matrix may compact excessively thus destroying the interparticle porosity. Ideally a compromise between these two extremes would constitute the best reservoir quality.

Stylolites in cores of the El Garia Formation from *Hasdrubal* commonly occur at bed boundaries and at the base of storm sheets. These surfaces facilitate dissolution migration and ultimately become sites of pressure solution. These boundaries have little permeability (except where fractured) and appear to partly compartmentalise the reservoir.

CONCLUSIONS

1. Nummulitic banks are common in Early and Middle Eocene Tethyan shallow-marine carbonates, especially in oligotrophic settings. In general, individual nummulite banks are dominated by only one or two species and show variations in both diversity and abundance of associated microfauna and macrofauna, reflecting varying degrees of oligotrophy and/or water energy.

2. A broad range of depositional geometries occur in nummulite accumulations from true banks with a depositional relief (up to a few metres) to flat "sheets". The original biofabric of the bank often exerts a fundamental control on reservoir quality, although subsequent diagenesis and bioturbation may obscure this trend.

3. Nummulitic limestones are important hydrocarbon reservoirs in North Africa (Tunisia and Libya), and have porosities of 10-26% and permeabilities of 40-100 md. Similar facies may constitute potential exploration targets in other areas such as Egypt, the Adriatic, Oman, Pakistan and India.

4. Nummulite deposits are complex and can best be understood by integrating both palaeoecological and sedimentological data. An understanding of the mode of formation of nummulite accumulations, and their likely distribution in space and time, are critical for the development of suitable models for future hydrocarbon exploration and development.

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