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Hydrodynamic behaviour of *Nummulites*: implications for depositional models

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Abstract Large benthic foraminifers are considered to be good indicators of shallow marine carbonate environments in fossil series. Over the last 50 years, the palaeoenvironment of Tertiary *Nummulites* accumulations has been a matter of debate, particularly because of difficulties in interpreting these deposits, and in this way, the absence of analogues in present-day seas does not help. The aim of this paper is to insight the different ways *Nummulites* tests and clasts may accumulate according to their hydrodynamic behaviour. Based on experimental measurements and on SEM observations, it appears that the high primary skeletal porosity of *Nummulites* made them easily transportable. The calculated threshold shear velocities confirm that large-sized *Nummulites* can be moved by weak wave-driven currents. This peculiar hydrodynamic behaviour of *Nummulites* could explain the diversity of depositional models. Depending on local hydrodynamic conditions, autochthonous *Nummulites* deposits can be preserved as in situ winnowed bioaccumulations or be accumulated offshore, onshore or alongshore, away from the original biotope.

Keywords Carbonates · Eocene · Large benthic foraminifera · Test density · Taphocoenosis

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Introduction

Nummulites accumulations occur in Late Palaeocene to Early Oligocene carbonate deposits, which represent about 30 Ma in the geological record. During this time, the marine microfauna were dominated by *Nummulites* along the Tethys palaeomargins. Some authors point out that the predominance of large benthic foraminifera (LBF) could be explained by the development of wide carbonate ramps and by warm seawater that induced nutrient deficiencies (Hallock 1985). This is supported by a major episode of global warming expressed by a 1.5‰ decrease in $\delta^{18}O$ which peaked during the Early Eocene Climatic Optimum (EECO) at 52–50 Ma (Kenneth and Scott 1991; Zachos et al. 2001).

Nowadays, the *Nummulites* limestones, which are extended from the West Pacific, to the Central Mediterranean, and to the Atlantic (Fig. 1), form important hydrocarbon reservoirs in the northern African of provinces (Tunisia and Libya). The reservoir qualities are mostly induced by the preservation of intraskeletal porosity of *Nummulites* tests. Numerous sedimentological studies have been made on these deposits in order to better understand the geometry of subsurface reservoirs (Arni 1965; Comte and Lehman 1974; Fournié 1975; Bishop 1985; Moody 1987; Bailey et al. 1989; Moody and Grant 1989; Bernasconi et al. 1991; Loucks et al. 1998; Anketell and Mriheel 2000; Racey et al. 2001; Jorry et al. 2003a,b; Vennin et al. 2003; Hasler 2004; Jorry 2004).

Various depositional models have been proposed, and most of them described *Nummulites* accumulations as banks, bars or low-relief banks, sometimes related to palaeo-highs. Previous studies have shown that LBF can be easily reworked by waves and currents (Davies 1970; Martin and Liddell 1991; Hohenegger and Yordanova 2001a,b; Yordanova and Hohenegger 2002), and several authors point out that the hydrodynamic behaviour of *Nummulites* is an important factor controlling their distribution (Aigner 1982; Fütterer 1982; Racey 2001). The unusual predominance of one group of organism associated to its peculiar hydrodynamic behaviour made

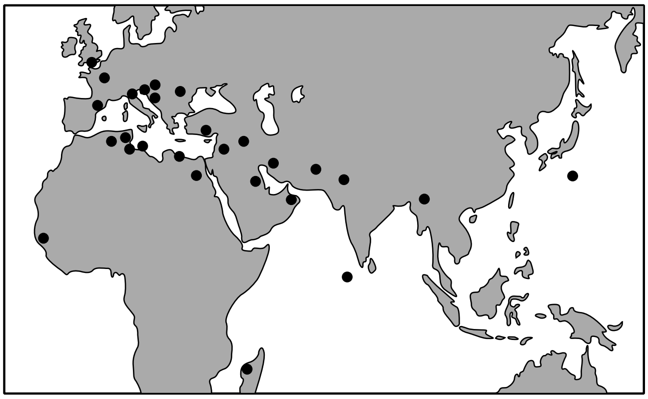


Fig. 1 Geographic distribution of the Eocene *Nummulites* carbonate deposits (modified from Racey 2001)

the *Nummulites* a very good example of taphonomic feedback regarding transportation and deposition (Kidwell and Jablonski 1983; Ginsburg 2005).

Nummulites reservoir facies are often associated with muddy and silt-sized facies composed of small debris (nummulithoclasts), which are mainly exported seaward (Loucks et al. 1998; Racey et al. 2001; Caline et al. 2003; Jorry et al. 2003a,b; Hasler 2004; Jorry 2004). Depending on the platform type (homoclinal ramp, rimmed shelf or platform with sharp slope breaks), the lateral facies variation is generally progressive and other subfacies rich in *Discocyclina* or *Operculina* may occur between *Nummulites* grainstones and nummulithoclastic packstones. In more proximal settings, nummulithoclasts are less abundant in the matrix of restricted/lagoonal muddy facies dominated by *Orbitolites*, *Alveolina*, and miliolids (Middle Eocene Dernah Formation, NE Cyrenaica; Jorry 2004). Nummulithoclasts clearly result from the reworking and the pulverization of *Nummulites*, but fragmentation processes remain unresolved. Loucks et al. (1998) suggested that bioturbation can be an important process for grain breakage. Beavington-Penney (2004) postulates that the fragmentation can also be the result of transportation of the tests within turbidity currents, and/or predation by relatively large bioeroders such as fish and echinoids.

The main objectives of this work are (1) to review the different depositional models which have been proposed in the literature, characterising the palaeoenvironment of *Nummulites*; (2) to present new measurements of the intraskeletal porosity, apparent density, and settling velocities of *Nummulites*, and to compare these results with those previously studied (Aigner 1982; Racey 2001); (3) to estimate the critical shear velocities of *Nummulites* of different sizes and densities, and to compare these values with wave shear velocities computed with the theoretical model developed by Madsen (1994); (4) to discuss the rare development or preservation of hydrodynamic sedimentary structures in these grain-supported sediments and (5) to propose an additional hypothesis regarding the preservation of complete *Nummulites* and the associated fragmentation processes which lead to the consequent nummulithoclast production.

Generalities on larger foraminifera

The palaeoenvironmental interpretation of carbonate rocks is significantly based on the presence or association of benthic fauna or microfauna, the life environment of which is particularly well documented in present-day seas. Unfortunately, there is no recent counterpart for the prolific accumulations of *Nummulites*, which appeared in the Late Paleocene, invaded the Tethyan margins during the Eocene and disappeared during the Middle Oligocene. The only recent form, *Palaeonummulites venosus*, restricted to the Indo-Pacific area, lives in marine environments with sandy bottoms between 20 and 85 m of water depth (Hohenegger et al. 1999, 2000; Hohenegger 2005). The maximum distribution is observed between 35 and 40 m (Langer and Hottinger 2000). Seven families of similar free-living LBF occur in modern carbonate systems including the porcellaneous forms (Archaiasinidae, Peneroplidae, Sorotidae and Alveolinidae) and the hyaline forms (Amphisteginidae, Calcarinidae and Nummulitidae). Species of these seven families are associated with endosymbionts that require light. The porcellaneous forms host rhodophytes, chlorophytes, dinoflagellates and diatoms, whereas the hyaline forms host only diatoms on living *Palaeonummulites venosus*, as identified by Leutenegger (1984).

Photoautotrophic symbionts are the only food source for LBF (Leutenegger 1984; Krüger 1994; Hohenegger 2004) and provide the potential for calcification of large skeletons (Hallock et al. 1991). Except for *Cycloclypeus carpentieri*, whose maximum observed diameter is 120 mm (Hohenegger et al. 2000), the gigantism which characterises Eocene *Nummulites* has no counterpart in present-day protist groups. The diameter of the largest *Palaeonummulites venosus* microsphere is 6.4 mm, and 3.2 mm for the largest macrosphere (Hohenegger et al. 2000), whereas fossil *Nummulites* often reach several centimetres in diameter. The largest size observed is reported by Nemkov (1962) who found, in Mesopotamia, specimens of *Nummulites millecaput* reaching 160 mm in diameter.

This great difference does create a problem in relating modern to ancient forms. Such gigantism is considered by Cowen (1983) as the proof of an active algal symbiosis. The probable role of symbionts in fossil *Nummulites* is also supported by the presence of microstructures similar to those observed in present-day forms, which provide shelter for symbionts and allow respiration (Bartholdy 2002). Moreover, Wells (1986), in discussing the control of stress in the environment on *Nummulites* ratios and sizes, points out that some foraminifers (such as *Elphidium*, *Ammonia*, and *Planorbulina*) can reproduce asexually in good environmental conditions and sexually during times of stress, when genetic diversity and dispersal are advantageous.

In the fossil record, several authors consider the shape and wall thickness of foraminiferal tests as a depth indicator (Kulka 1985; Eichenseer and Luterbacher 1992; Loucks et al. 1998; Racey 2001; Jorry et al. 2003b; Vennin et al. 2003; Hasler 2004; Jorry 2004). This assumption is based on observations of LBF from present-day environments.

Larsen (1976) and Larsen and Drooger (1977) found that *Amphistegina* showed a strong inverse relationship between test thickness and habitat depth. Similar data reported by Hallock (1979) for two Pacific sites confirm the tendency for thicker-tested forms in shallow, more turbulent environments, and thinner-tested forms in low-energy and/or deeper environments. This relationship has also been demonstrated for other foraminifers such as *Heterostegina depressa* (Hottinger 1973) and for operculinid foraminifera in general (Hottinger 1973; Pecheux 1995; Yordanova and Hohenegger 2004; Renema 2005). Experimental work (Hallock 1979, 1981; Hallock et al. 1986) shows that both light and water motion directly influence test thickness and shape in *Amphistegina* by controlling the thickness of individual lamellae as they form.

Classically, *Nummulites* are believed to have formed autochthonous banks or bioherms, and they are even considered to be reef-builders (Arni 1965). According to Loucks et al. (1998), these deposits are not high-profile or relief banks (they have no steep slopes or landward dipping strata), and they formed in moderately low-energy environments between fair-weather and storm wave base. More recently, it has been recognised that *Nummulites* occur reworked in high-energy environments such as shoals, fore-reef-channels and storm deposits (Racey 2001; Hasler and Davaud 2001; Jorry et al. 2003b; Jorry 2004). From a sedimentological point of view, nummulite-rich facies may result from three distinct processes: (1) the representation of the undisturbed record of a prolific biocoenosis, (2) the accumulation of tests transported by wave- or tide-induced currents and (3) the residual concentration of tests after repeated winnowing events (Aigner 1985).

The distinction between these three depositional modes is essential for understanding the geometry and petrophysical properties of potential reservoir rocks. Undisturbed biocoenoses are characterised by packstone to wackestone textures, with well-preserved encrustations only on one side (Racey 2001), and show a wide faunal diversity (i.e., red algae, echinoderms, gastropods, bryozoans, bivalves and small benthic foraminifers). The life position, which is often used as a reliable criterion for autochthony, is not well documented for *Nummulites*. Two contradictory possibilities have been suggested: *Nummulites* were lying on the sea floor or attached on seagrass leaves; the second possibility is not observed for the living *Nummulites venosus* in the present-day seas. This could explain the preferential encrustation on one side of the test (Racey 2001). For Deeke (1914) and Rozlozsnik (1927) however, the symmetric and regular form of most of the tests indicate a vertical life position.

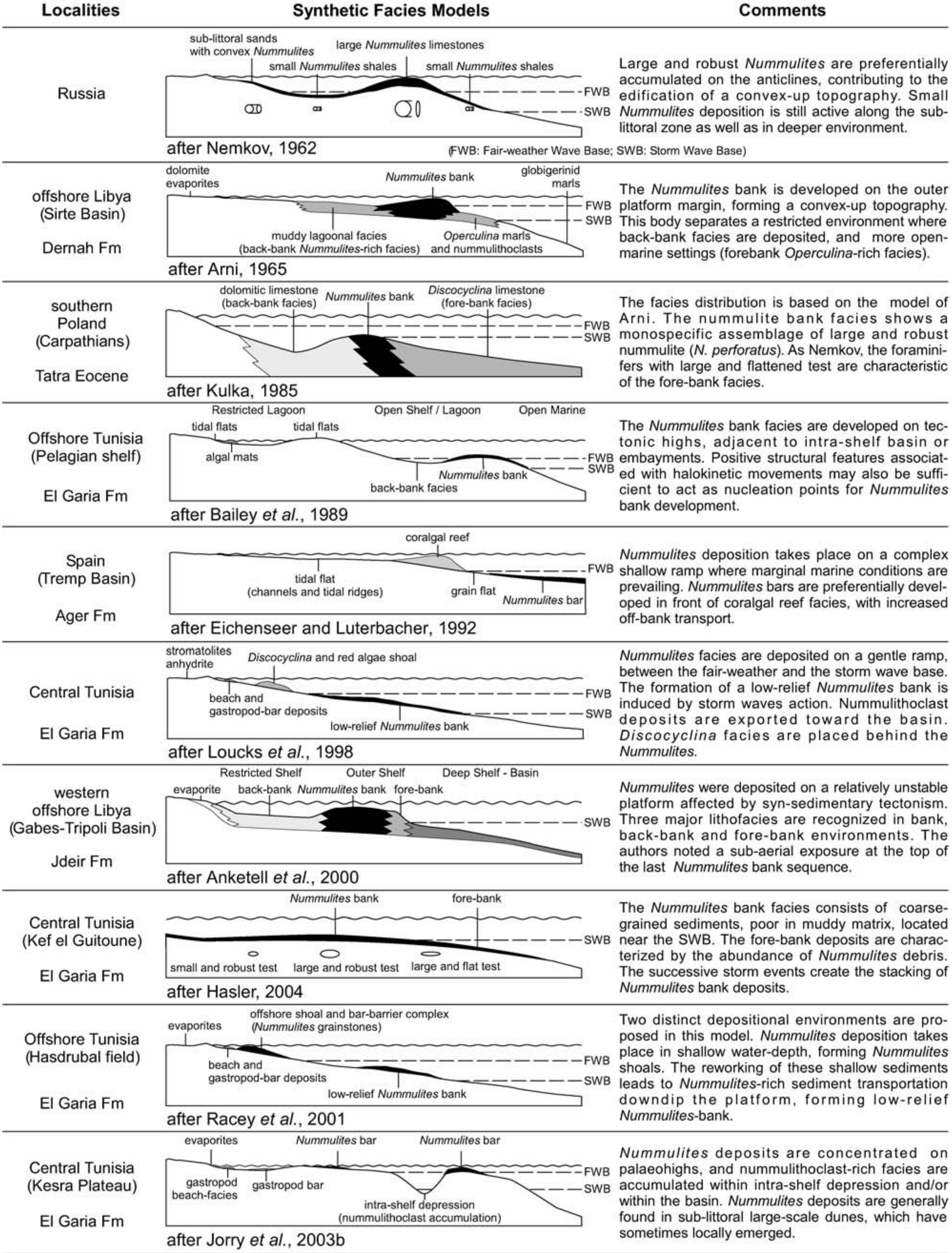
By contrast, taphocoenoses resulting from transportation or in situ winnowing, are characterised by more or less monospecific assemblages and grain-supported textures. Sedimentary structures, which should be omnipresent in high-energy deposits, have been rarely documented from field or core studies. Aigner (1982) pointed out the presence of "reminiscent cross-bedding stratification," small-scale scours and fill structures and *Nummulites* imbrications in the *Gizehensis* bed of Egypt. Jorry et al. (2003b) mentioned the presence of large-scale cross bedding in the Eocene El Garia Formation in central Tunisia. However, most of the time, grain-supported facies show a rather chaotic pattern and no obvious sedimentary structures. This explains why the *Nummulites* accumulations have commonly been considered as biocoenoses even though the absence of a matrix often indicates high-energy depositional processes. The reasons for the scarcity or the poor expression of hydrodynamic structures will be discussed later.

A complete review regarding the ecology of extant nummulitids and other LBF has been recently published by Beavington-Penney and Racey (2004) and by Hohenegger (2004), who provided a detailed discussion on depth coenoclines and environmental considerations regarding LBF from the western Pacific.

Diversity of depositional models in the fossil record

Several depositional models have been proposed to characterise the nummulite-rich accumulations (Fig. 2). In most of these case studies, the deposition of *Nummulites* sediment is located around palaeo-reliefs (sedimentary or structural highs) or along homoclinal carbonate ramps. Different palaeo-depths are envisaged, from 10 to 60 m depth, and different depositional reliefs are described:

- *Nummulites* banks that form convex-up structures. The so-called "bank" structure was first described by Nemkov (1962) and Arni (1965). These banks, which are characterised by a mono-specific association of *Nummulites*, separate a restricted area (back-bank environment) from an open marine zone (fore-bank settings). This model has been applied to the Tatra Eocene of Poland (Kulka 1985), to the Middle Eocene build-ups in Egypt (Aigner 1983), and to the Jdeir Formation in offshore Libya (Anketell and Mriheel 2000)
- Low-relief banks or sheets which are developed along a broad, gently dipping homoclinal ramp (Comte and Lehman 1974; Loucks et al. 1998; Moody et al. 2001; Hasler 2004). The petrographic composition of the sedimentary body is controlled by physical processes such as winnowing of both the matrix and smaller A-forms (Aigner 1982, 1985; Racey 2001). The resulting sedimentary textures, including size-sorting, packing and imbrication of the tests, indicate para-autochthonous to allochthonous deposits. However, Wells (1986) and Loucks et al. (1998) consider that *Nummulites* monospecific deposits may rather result from biofactors such as environmental stresses. Imbrications can also be due to post-depositional processes such as bioturbation or burrowing (Loucks et al. 1998).
- Shoals formed in proximal up-ramp settings (Racey et al. 2001). This facies, showing large-scale cross-bedding structures, can be observed in central Tunisia (Jugqurta and Kesra Plateau; Jorry et al. 2003b; Jorry 2004);
- *Nummulites* "bars" developed in very shallow environments in front of coralgal reefs bordering a carbonate ramp system (Eichenseer and Luterbacher 1992). This



Localities	Synthetic Facies Models	Comments
Russia	after Nemkov, 1962 (FWB: Fair-weather Wave Base; SWB: Storm Wave Base)	Large and robust *Nummulites* are preferentially accumulated on the anticlines, contributing to the edification of a convex-up topography. Small *Nummulites* deposition is still active along the sub-littoral zone as well as in deeper environment.
offshore Libya (Sirte Basin) Dernah Fm	after Arni, 1965	The *Nummulites* bank is developed on the outer platform margin, forming a convex-up topography. This body separates a restricted environment where back-bank facies are deposited, and more open-marine settings (forebank *Operculina*-rich facies).
southern Poland (Carpathians) Tatra Eocene	after Kulka, 1985	The facies distribution is based on the model of Arni. The nummulite bank facies shows a monospecific assemblage of large and robust nummulite (*N. perforatus*). As Nemkov, the foraminifers with large and flattened test are characteristic of the fore-bank facies.
Offshore Tunisia (Pelagian shelf) El Garia Fm	after Bailey *et al.*, 1989	The *Nummulites* bank facies are developed on tectonic highs, adjacent to intra-shelf basin or embayments. Positive structural features associated with halokinetic movements may also be sufficient to act as nucleation points for *Nummulites* bank development.
Spain (Tremp Basin) Ager Fm	after Eichenseer and Luterbacher, 1992	*Nummulites* deposition takes place on a complex shallow ramp where marginal marine conditions are prevailing. *Nummulites* bars are preferentially developed in front of coralgal reef facies, with increased off-bank transport.
Central Tunisia El Garia Fm	after Loucks *et al.*, 1998	*Nummulites* facies are deposited on a gentle ramp, between the fair-weather and the storm wave base. The formation of a low-relief *Nummulites* bank is induced by storm waves action. Nummulithoclast deposits are exported toward the basin. *Discocyclina* facies are placed behind the *Nummulites*.
western offshore Libya (Gabes-Tripoli Basin) Jdeir Fm	after Anketell *et al.*, 2000	*Nummulites* were deposited on a relatively unstable platform affected by syn-sedimentary tectonism. Three major lithofacies are recognized in bank, back-bank and fore-bank environments. The authors noted a sub-aerial exposure at the top of the last *Nummulites* bank sequence.
Central Tunisia (Kef el Guitoune) El Garia Fm	after Hasler, 2004	The *Nummulites* bank facies consists of coarse-grained sediments, poor in muddy matrix, located near the SWB. The fore-bank deposits are characterized by the abundance of *Nummulites* debris. The successive storm events create the stacking of *Nummulites* bank deposits.
Offshore Tunisia (Hasdrubal field) El Garia Fm	after Racey *et al.*, 2001	Two distinct depositional environments are proposed in this model. *Nummulites* deposition takes place in shallow water-depth, forming *Nummulites* shoals. The reworking of these shallow sediments leads to *Nummulites*-rich sediment transportation downdip the platform, forming low-relief *Nummulites*-bank.
Central Tunisia (Kesra Plateau) El Garia Fm	after Jorry *et al.*, 2003b	*Nummulites* deposits are concentrated on palaeohighs, and nummulithoclast-rich facies are accumulated within intra-shelf depression and/or within the basin. *Nummulites* deposits are generally found in sub-littoral large-scale dunes, which have sometimes locally emerged.

Fig. 2 Comparison between different facies models proposed for interpreting the *Nummulites* accumulations

model has been proposed for the Ager Formation in the south Pyrenees foreland basin (Spain).

Depending on the model, *Nummulites*-rich sediments are considered to be autochthonous deposits (biocoenoses) or para-autochthonous to allochthonous deposits (taphocoenoses), resulting from landward or seaward transportation. This diversity could be due to the configuration of the platform (type of depositional profile and irregularities of the sea floor), to adaptive life strategies of *Nummulites* according to changes in local light or hydrodynamic conditions and/or to the ability of the tests to be transported seaward or landward by storm- or tide-induced currents.

Although no equivalent accumulations of giant foraminifer tests can be observed in present-day seas, studies of modern benthic foraminifera confirm that the transportation of living and dead tests could have a significant impact upon the distribution of many species (Murray et al. 1982; Chapman and Jones 1986; Murray 1987; Davaud and Septfontaine 1995; Hohenegger and Yordanova 2001a). However, the hydrodynamic behaviour of modern benthic foraminifera has received some attention. Dead benthic foraminiferal tests can be found in suspension in the water column, as reported by Poizat (1970), Blanc-Vernet et al. (1979), Murray et al. (1982), Murray (1987) and Davaud and Septfontaine (1995). The first consequence is that the distribution of tests is largely controlled by dominant marine currents, i.e., storm or tide-induced currents.

Long-distance transportation of the tests could be facilitated by the presence of trapped gases in the internal structure of the tests, which may confer very low densities. The presence of gases within foraminiferal chambers of dead organisms results from the decay of the organic material after the cell's death (Severin and Lipps 1989). This idea is supported by the fact that foraminifera may retain protoplasm for weeks or months after death (Bernhard 1988; Hannah and Rogerson 1997; Alve and Olsgard 1999). In the present-day, the presence of dead protoplasm within tests can be attributed to either a disease, or an adverse environmental change (Murray and Bowser 2000). Moreover, if dead foraminifers are transported towards intertidal environments, tests could be dried out during low tide and easily picked up later by the incoming tide or the wind when the chambers remain filled up with air (Thomas and Schafer 1982; Davaud and Septfontaine 1995). Wang and Murray (1983) noticed a close correlation between the magnitude of the tides and the abundance of small transported foraminiferal tests. Concerning living foraminifers, their ability to be moved by currents may also depend on the nature of the fluid that filled the porous network. For example, living forms such as *Alveolinella quoyi* have enough organic material to fill only about 39% of their chamber space in the ultimate whorl. If this space if partly filled up with gases (O_2 produced by photosymbionts and CO_2 resulting from respiration), overall test density decreases and the test can be easily moved (Severin and Lipps 1989).

The ability of Eocene *Nummulites* to be transported has already been suggested by several authors (Wells 1984, 1986; Loucks et al. 1998; Racey 2001), but the hydrodynamic behaviour of *Nummulites* remains poorly documented. Aigner (1982) cites density measurements made on *Nummulites* going down to 1.28 g/cm^3 and flume experiments conducted by Fütterer (personal communication), who found threshold velocities ranging from 18 to 77 cm/s. More recently, Racey (2001) mentions an internal report from British Gas in which critical shear velocities were computed for large B-form *Nummulites* with a residual porosity reaching 40%. The low values obtained (7 cm/s) led this author to conclude that "*Nummulites* bank material could easily be moved in the outer shelf. . .". The aim of our paper is to give additional evidence concerning the hydrodynamic behaviour of *Nummulites* which could explain the diversity of the depositional environments in the fossil record.

Methodology

This work is based on the observations made on samples from outcrops and subsurface which include 1,200 thin sections, SEM observations and 40 porosity measurements (mercury, microtomography and image analysis). Different locations have been investigated in Spain (Tremp Basin), Tunisia (outcrops of the Kesra Plateau, Djebel Ousselat and Kef El Garia, onshore concession of Sit El Itayem), and Libya (outcrops from NE Cyrenaica, C137 license in NW offshore zones operated by Total).

The SEM was used to characterise the micropores of *Nummulites* tests. Partially silicified *Nummulites* were dissolved, and resulting non-dissolved silicified fragments were selected for the analysis. The quantification of the macroporosity was obtained by coupling X-ray microtomography (120 equatorial sections of a 1.5-cm-thick *Nummulites*), computer image analysis and point counting on thin sections.

Apparent densities of selected, isolated *Nummulites* were deduced from measurements of their weight and volume obtained by immersion within mercury (Hg). Hg was used because it is a non-wetting fluid which allows no imbibitions within the porous network. The method was first calibrated using a pure calcite crystal.

Settling-velocity measurements were performed on 33 fossil *Nummulites* that have been collected in Cyrenaica (NE Libya). *Nummulites* were selected according to size, ranging from 4 to 32 mm of diameter; types (micro- and megalo-spherical) and characterised by minimum diagenetic modifications and well-preserved intraskeletal porosity. The shape parameters these specimens (longest, intermediate and shortest orthogonal axis of the test) and apparent density (weight divided by external volume) were measured. The settling-velocities were measured at a distance of 1.50 m, in a transparent plastic tube of 40 cm diameter, and the water salinity was adjusted to 32 g/L. The water temperature, which exerts a significant influence on the settling-velocity by changing its density and dynamic viscosity (Bolton and Havenhand 1997), was successively adjusted to 10, 20, and 26.5°C. The measurements were

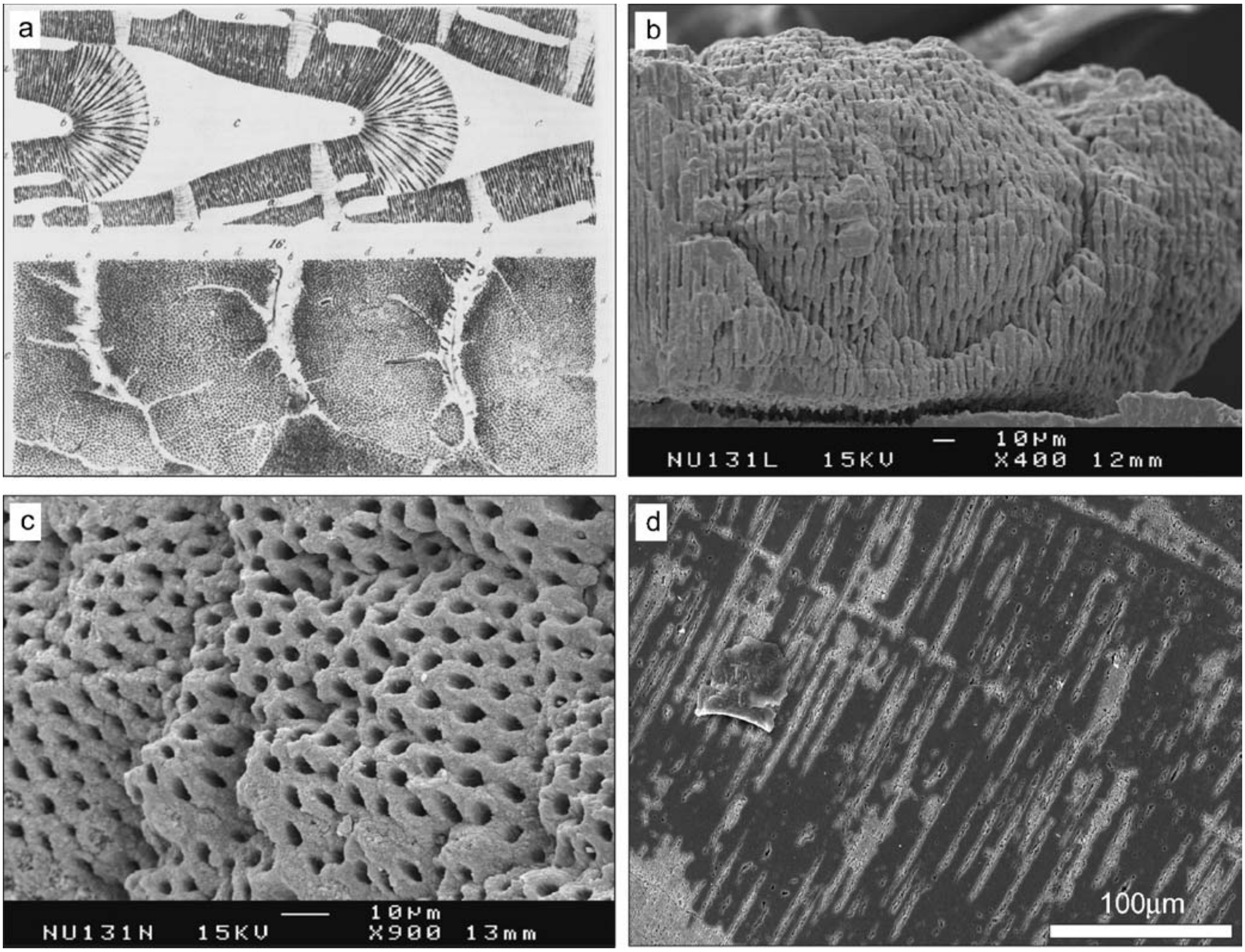


Fig. 3 Internal structure of fossil *Nummulites* tests. **a** Illustration of the microporous test of *Nummulites laevigatus* (according to Carpenter 1850). **b–c** SEM microphotographs of the microporous walls of silicified *Nummulites* sp. (Figols Formation, Spain). **d** SEM microphotograph of a polished slab through two successive *Nummulites* turns, showing that the tubular holes (here filled with calcite) are connected between the turns

repeated alternatively on “full-water” (water injection) and “full-air” (air drying) *Nummulites*.

Finally, theoretical settling-velocities were calculated using equations proposed by Le Roux (1997) and compared with experimental values. We have chosen not to use present-day *Palaeonummulites venosus* in our measurements because the morphological parameters (size and thickness) of living species differ significantly from the Eocene *Nummulites* which developed a much larger size.

Results

Porosity and apparent density measurements

Primary, intraskeletal porosity may be a significant part of the total porosity in *Nummulites*-dominated reservoirs. *Nummulites* tests contain abundant chambers (macroscopic porosity) and a dense network of micropores developed inside the chamber walls.

These micropores were detected by Carpenter (1850) and confirmed by Schaub (1981) who described perforations in the walls of *Nummulites* (Fig. 3a). The role of these microstructures is not explained in regards to the fossil *Nummulites*, but in modern environments, many foraminifera develop perforations for gas exchange, in particular of O_2 and CO_2, through the wall (Leutenegger and Hansen 1979). Gas exchange is of particular significance when foraminifera are associated with endosymbiotic algae, which develop light-regulation devices in order to avoid photo-inhibition (Hottinger 2000). However, this microporous network can become rapidly and partially sealed after the cell’s death, due to the precipitation of early marine cement within chambers.

The quantification of the porosity amount of this microporous network was achieved by image analyses of SEM pictures of etched silicified *Nummulites* from the Eocene Figols Formation (Spain). These micropores have 1–2 µm diameters, and consist of tubular holes perpendicular to the wall surface (Fig. 3b–d) that range from 25 to 36% of

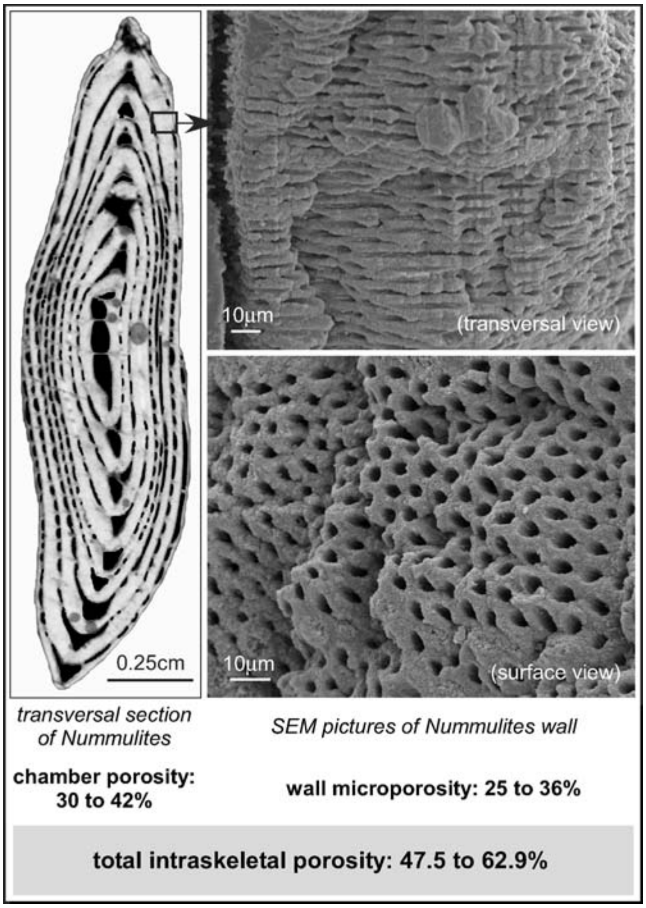


Fig. 4 Quantification of the intraskeletal porosity (chambers and walls) of *Nummulites gizehensis*. Porosity values were obtained on numerous sections of *Nummulites* using image analysis (thin sections and SEM) and X-ray microtomography

the wall volume. The porosity of chambers, estimated by image analysis of successive microtomographic sections and by point-counting on thin sections, ranges from 30 to 42% (Fig. 4). As a consequence, the total porosity of *Nummulites* varies from 47.5 to 62.9%. These results are very similar to those obtained for living foraminifera; porosity measurements on *Amphisorus* are as high as 72% (Aigner 1982).

The measured apparent density values of *Nummulites* range from 1.48 to 2.61 g/cm^3 (Table 1). This large range of density is due to the presence of cement which partly seals intraskeletal porosity. Taking into account that benthic hyaline tests are mainly composed of low magnesium calcite (LMC), according to our measurements of *Paleonummulites venosus* from Papua New Guinea and to previous work published by Debenay et al. (1999), the same mineralogical composition is expected for Eocene *Nummulites* tests. The apparent density (ρ_s) of *Nummulites* can be established as a function of intraskeletal porosity (φ), LMC density (ρ_LMC) and internal fluid density (ρ_fluid) via this equation:

$$\rho_\mathrm{s} = (1-\varphi)\rho_\mathrm{LMC} + \varphi\rho_\mathrm{fluid}$$

Since after the cell's death, chambers may be filled up with seawater or gas (produced by the decay of organic material), two functions can be adjusted (Fig. 5). Using the previous formula, the apparent density of *Nummulites* ranges from 1.7 to 1.9 g/cm^3 when the porous network is filled with seawater. Infilling gases induced a drastic fall of the apparent densities (1.1–1.4 g/cm^3). These low values suggest that *Nummulites* tests can be transported as a suspended load, as observed for several modern species of benthic foraminifers (Poizat 1970; Blanc-Vernet et al. 1979; Murray et al. 1982; Murray 1987; Severin and Lipps 1989; Davaud and Septfontaine 1995).

The hydrodynamic behaviour of *Nummulites*

Fossil *Nummulites* are known as having developed a large range of shapes induced by reproductive strategies (small sexual A-forms and large asexual B-forms) and by environmental factors (light intensity and hydrodynamic conditions) which significantly control the size, shape and thickness of the tests (Hallock 1979, 1981; Hallock et al. 1986; Hohenegger et al. 2000). The hydrodynamic behaviour of *Nummulites*, which depends on their size, shape and density, is a fundamental parameter controlling their transport.

The estimation of critical shear velocities of *Nummulites* was made using the equations and the Excel program developed by Le Roux (1997). This program computes the critical shear velocity (U_c^*) from the particles shape parameters (D_l, D_i, D_s: longest, intermediate and shortest orthogonal axis of the particle; cm) or from measured settling velocities (W_m). Thirty-three *Nummulites* of different size and density, and with the intraskeletal porosity partly preserved, were selected and their settling velocities were measured in a 2-m-high settling tube filled with seawater. These data were used as input to compute the critical shear velocities (Table 1). The values obtained from shape parameters (U_cs^*) show a good correlation with those obtained from measured settling velocities U_cw^* (Fig. 6), but they are systematically higher. As the measured settling velocity is a hydrodynamic behavioural measure incorporating the effects of particle size, shape and density (Le Roux 1997), it seems reasonable to consider the values derived from the settling velocities as more realistic. Unfortunately, it is not possible to find *Nummulites* in which the primary intraskeletal porosity has been totally preserved. The only way to estimate the critical shear velocities of *Nummulites* is to compute them from geometrical parameters and apparent densities obtained from porosity estimations (Fig. 5).

According to the data presented in Table 1, the equations proposed by Le Roux (1997) have been slightly modified to take into account the specific hydrodynamic behaviour of *Nummulites*. The critical shear velocity U_c^* becomes:

$$U_\mathrm{c}^* = 1.959 + 0.253\sqrt{\beta g\left(\frac{\sqrt[3]{D_\mathrm{i}D_\mathrm{l}D_\mathrm{s}}}{1.32}\right)\frac{(\rho_\mathrm{s}-\rho_\mathrm{f})}{\rho_\mathrm{f}}}$$

Table 1 Shape parameters (D_l, D_i, D_s: large, intermediate, small diameter), density, settling velocity measured on *Nummulites*. Critical shear velocities (U_c^*) have been computed by using the equations of Le Roux (2001)with the shape parameters and density as input for U_{cs}^* and the measured settling velocity as input for U_{cw}^*. Calculation of equivalent quartz grain diameter shows that a *Nummulites*-rich deposit behaves like coarse sands (1.1 mm) to fine gravels (5.0 mm)

Samples	Sexual generation	*Nummulites*			Measured settling velocity W_m (cm/s)	U_{cs}^* computed from D_l, D_i, D_s and ρ_s (cm/s)	U_{cw}^* computed from W_m (cm/s)	Equivalent quartz grain diameter (mm)
		Shape and size parameters D_lD_i (mm)	D_s (mm)	Density ρ_s (g/cm^3)				
SJ10	B-form	25.2	4.8	2.33	28.2	7.8	3.9	2.9
SJ11	B-form	28.3	7.4	2.28	40.3	8.5	5.1	5.0
SJ12	B-form	29.1	6.5	2.51	32.4	9.2	4.4	3.7
SJ14	B-form	30.7	6.6	2.58	35.6	9.6	4.7	4.2
SJ15	B-form	32.2	6.9	2.58	33.7	9.8	4.5	3.9
SJ18	B-form	25.8	4.5	2.31	25.1	7.7	3.6	2.5
SJ19	B-form	26.8	5.6	2.47	32.3	8.6	4.4	3.7
SJ21	B-form	31.5	6.6	2.40	31.2	9.1	4.2	3.4
SJ22	B-form	26.3	3.6	2.45	23.4	7.9	3.4	2.2
SJ23	B-form	27.7	5.6	2.42	28.2	8.5	3.9	2.9
SJ24	B-form	22	4.4	2.58	27.6	8.0	3.9	2.9
SJ25	B-form	21.1	5.3	2.42	27.0	7.7	3.8	2.8
SJ26	A-form	11.6	4.8	2.31	31.9	6.0	4.3	3.5
SJ27	B-form	21.5	4	2.39	28.8	7.4	4.0	3.1
SJ28	A-form	10.5	3.1	2.19	23.1	5.1	3.3	2.1
SJ29	A-form	12.2	4.4	2.38	22.8	6.2	3.3	2.1
SJ30	A-form	8.1	4	1.95	26.2	4.4	3.6	2.5
SJ31	A-form	7	3.6	2.32	23.9	4.8	3.5	2.3
SJ32	A-form	6.6	2.9	1.99	25.5	3.9	3.6	2.5
SJ33	A-form	6.8	2.7	1.48	19.9	2.7	2.8	1.5
SJ34	A-form	7	2.4	1.48	19.6	2.7	2.7	1.4
N3b	B-form	20.3	3.3	2.28	20.2	6.7	3.0	1.8
SJ710	B-form	24.7	4.7	2.19	24.1	7.3	3.4	2.2
SJ724-2	B-form	30.4	5.5	2.37	27.0	8.7	3.8	2.8
N2a	B-form	20.6	4.2	2.01	19.7	6.2	2.9	1.6
N2b	B-form	16.5	2.9	2.05	19.4	5.5	2.9	1.6
SJ668	B-form	20.8	6.6	2.24	30.5	7.5	4.1	3.2
SJ724-1	B-form	21.7	5.5	2.61	27.1	8.4	3.9	2.9
SJ10	A-form	12.6	3.7	2.57	26.2	6.5	3.8	2.8
SJ7	A-form	5.1	2.52	2.57	21.7	4.5	3.2	2.0
SJ3	A-form	5.2	1.9	2.03	15.3	3.5	2.3	1.1
SJ5	A-form	5	2	1.80	15.8	3.0	2.4	1.2
SJ6	A-form	5	2.4	2.54	20.2	4.4	3.0	1.8

where β, the dimensional critical shear stress is derived from W_d, the dimensionless sphere settling velocity, and D_d, the dimensionless size of the equivalent sphere using the following equations:

$$\beta = -0.0717 \ \log_{10}(W_d) + 0.0625$$

$$\text{for } W_d < 2.5$$

$$\beta = 0.029 + 0.003W_d - 9.935 \times 10^{-5} W_d^2$$

$$\text{for } W_d > 2.5$$

$$W_d = -0.375 + 0.29D_d - 0.002D_d^2 + 4.731 \times 10^{-6} D_d^3$$

$$\text{for } D_d < 134.9$$

$$W_d = \sqrt{2.531D_d + 160} \qquad \text{for } D_d > 134.9$$

D_d is directly linked to the shape and size of *Nummulites*, D_l, D_i, D_s (cm), to the apparent density of *Nummulites* and seawater, ρ_s and ρ_f (g/cm^3), to the dynamic viscosity of seawater. μ (g/cm/s), and to the gravity constant, g (cm/s^2):

$$D_d = \sqrt[3]{D_i D_l D_s} \cdot \sqrt[3]{\rho_f g \frac{(\rho_s - \rho_f)}{\mu^2}}$$

The obtained threshold shear velocities confirm that pluricentimetre-scale *Nummulites* can easily be moved by wave-driven currents (Fig. 7a). Large B-form *Nummulites* (2 cm in diameter) with an apparent density of 1.8 g/cm^3

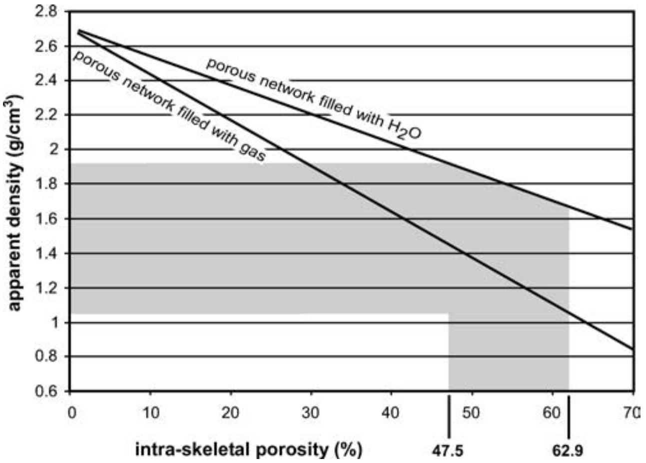


Fig. 5 Relationship between the intraskeletal porosity and the apparent density of *Nummulites*. The *grey area* represents the estimated range of porosity and the corresponding apparent density

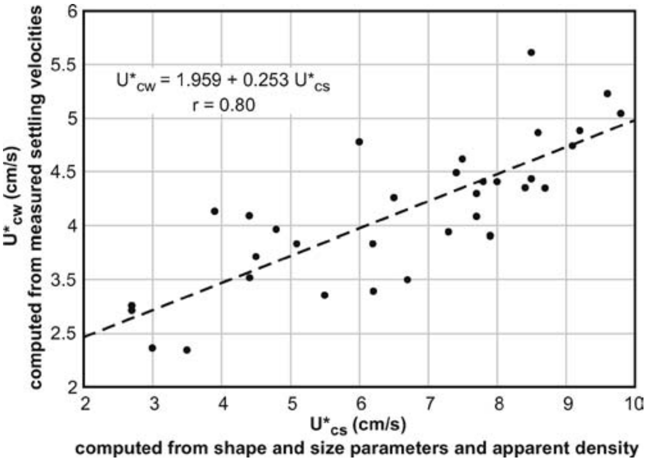


Fig. 6 Correspondence between threshold shear velocities, computed from size parameters and density (U^*_{cs}), and threshold shear velocities derived from measured settling velocities (U^*_{cw}) using the algorithm developed by Le Roux (1997). *r* correlation coefficient

are transported when the shear velocity reaches 3.3 cm/s (Figs. 5 and 7a). These values are about half of those proposed by Racey (2001), who used a flume-tank. Correspondence with quartz grains having equivalent threshold shear velocities shows that *Nummulites* behave as quartz grains of one-tenth to one-twentieth of their diameter (Table 1). By comparison with other carbonate particles, it is demonstrated from flume and settling-tube experiments that segments and fragments of segments of crinoids are hydraulically equivalent to quartz grain one-tenth of their diameter (Savarese et al. 1996; Ginsburg 2005).

Such shear velocities may occur at variable depth, depending on the length, the period and the height of waves. Using present-day wave parameters observed on a modern ramp along the coastline of Texas (station 42020, National Data Buoy Center), we computed the wave-shear velocities for increasing water depth with the program proposed by Sherwood (2004), based on the equations established by Madsen (1994). The obtained values indicate a potential reworking of large B-form *Nummulites* (2 cm in diameter, density of 1.8 g/cm^3) down to 50 m depth, which suggests a large range of possible depositional environments (Fig. 7b). If chambers are filled with gas, the potential reworking depth may reach 60 m water depth (Figs. 5 and 7b). Considering that *Nummulites* may have lived in the lower photic zone (in comparison with a depth range of 30 to 80 m for the modern *Palaeonummulites venosus*), the test can be transported far away from the original biotope

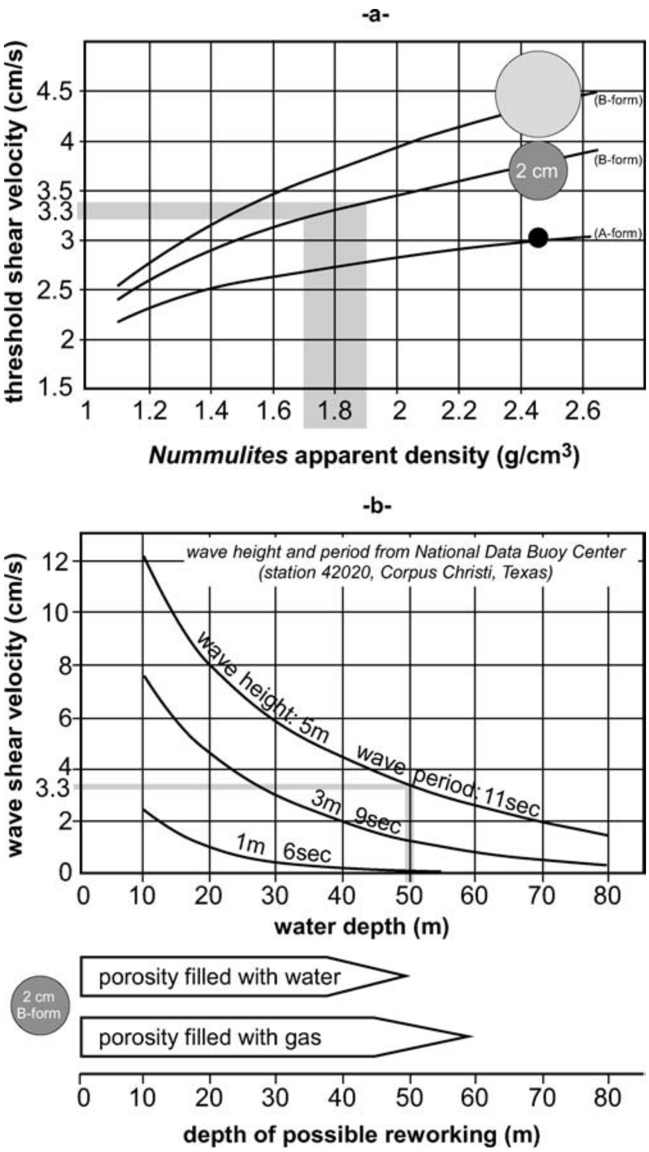


Fig. 7 **a** Relation between the apparent density of *Nummulites* of different sizes and computed threshold shear velocity. *Gray area* points out that a 2 cm B-Form *Nummulites*, whose intraskeletal porosity (ranging from 47.5 to 62.9%) is filled with seawater, can be transported when the threshold shear velocity reaches 3.3 cm/s. **b** Relation between the water depth and the predicted bottom-wave shear velocities for different wave heights and wave periods. The *grey line* indicates that the same large B-form *Nummulites* (2 cm in diameter, filled with seawater) can be moved down to a 50 m depth during storm conditions. If the intraskeletal porous network is filled with gas, they can be moved down to a 60 m water depth

after the cell's death. The distance of transportation also depends on the density of *Nummulites*, which is controlled by the intraskeletal porosity and by the nature of the fluid within their chambers (seawater or gas).

Discussion: implications in depositional processes

Rare preservation of sedimentary structures

In *Nummulites* facies, high-energy sedimentary structures are rarely developed or preserved, although all depositional models place the *Nummulites* accumulations between the fair-weather and the storm wave base. This paradox is explained as follows:

- The *Nummulites* accumulation results from a high prolific biocoenose and is not affected by bottom currents as suggested by Nemkov (1962), Arni (1965), Kulka (1985) and Anketell and Mriheel (2000)
- The *Nummulites* accumulations are controlled by a reworking processes, but high-energy primary structures are destroyed by bioturbation, which is often observed (Moody and Grant 1989; Loucks et al. 1998; Moody et al. 2001; Racey 2001; Racey et al. 2001)
- The *Nummulites* deposits are formed in low-energy environments, i.e., either below the storm wave base or in a protected area that could have been created by the presence of a physical barrier or by the presence of dense seagrass meadows (Blondeau 1972).

Our experimental approach indicates that *Nummulites* of different sizes may have the same hydrodynamic behaviour depending on their shape, on the nature of the fluids filling the internal porosity and on the degree of early intraskeletal cementation (Fig. 8). Consequently, *Nummulites* of different sizes can be transported and deposited simultaneously, and the detection of sedimentary structures, which relies on the presence of subtle granulometric contrasts, will be difficult or even impossible.

This could explain why hydrodynamic sedimentary structures are so rare in *Nummulites*-rich facies. They can be occasionally detected when bioclastic sands are enriched with quartz or argillaceous particles which may form drapes emphasising stratifications. In central Tunisia (Kesra Plateau, El Garia Formation), where large-scale dunes composed of large microspherical forms have been observed, the sedimentary structures are highlighted by solution seams, accentuating the original bedding (Jorry et al. 2003b; Jorry, 2004).

Preservation and fragmentation of *Nummulites* tests

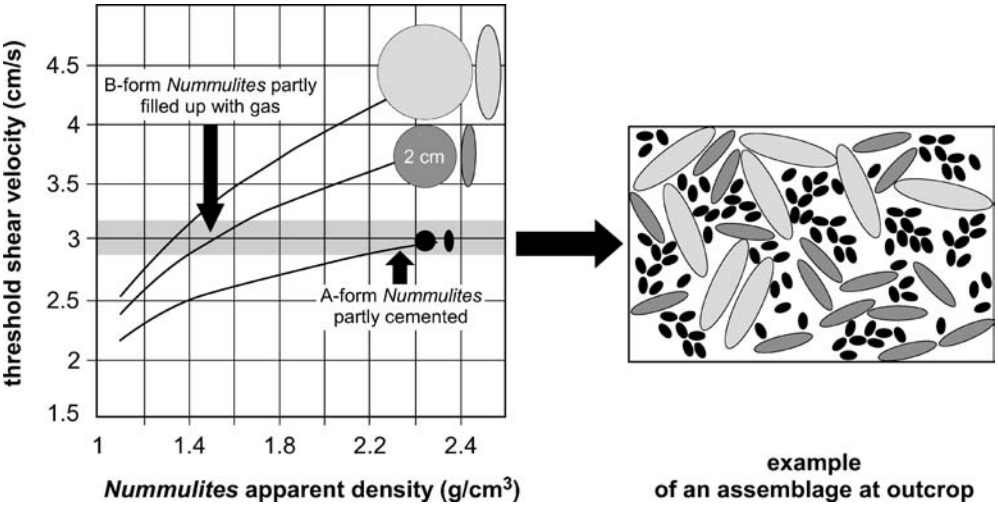
The *Nummulites* carbonate production often is associated with the production of significant amounts of nummulithoclasts in North Africa, especially in Tunisia. These silt-sized particles were either exported down slope or may partially constitute the matrix of the inner ramp deposits, and we rarely observe intermediate granulometry between complete *Nummulites* and silt-sized nummulithoclastic particles.

Fragmentation processes are still a matter of debate, and they cannot only be dependent on the distance of transportation. Severin and Lipps (1987) clearly demonstrate that living *Alveolinella quoyi* tests are relatively resistant to damage by abrasion. Beavington-Penney (2004) shows that it is impossible to reproduce in *Palaeonummulites venosus* the degree of test damage seen in fossil forms, despite simulating transport up to approximately 71 km. Kotler et al. (1992) experimentally tested the abrasion of selected modern foraminifers (including *Amphistegina gibbosa*, *Archaias angulatus*, *Peneroplis proteus* and *Sorites orbiculus*), and observed that pitting of the surface was the most common feature produced, even after 1,000 h of abrasion (corresponding very approximately to several hundred kilometres of transport). Beavington-Penney (2004) suggests that the formation of nummulithoclasts may result from the predation by large bioeroders such as fish and echinoids.

However, based on the SEM study of modern carbonate sediments from New Caledonia and French Polynesia, Debenay et al. (1999) demonstrate that the breakdown of foraminiferal tests can produce a noticeable part of the carbonate mud content. The mechanical erosion in high-energy environments is favoured by biological activity such as partial dissolution in predator guts (Hickman and Lipps 1983), and by bioerosion by boring algae, fungi and sponges (Kloos 1982). In the present-day dead benthic foraminifers that we collected in loose superficial sediment, fringes of early marine cements are also frequently observed (Fig. 9a,b). Similar thin fringes of cement lining the chambers are often present in well-preserved *Nummulites* from central Tunisia and more significantly in northern Cyrenaica *Nummulites* shell beds (Fig. 9c,d). The pre-depositional character of this cement for the Eocene *Nummulites* is attested by its absence of interparticle pore spaces (Fig. 9d). This early precipitation of cement within the internal structures of *Nummulites*, slightly increases the test density and their settling velocity. Consequently, *Nummulites* containing internal fringes are expected to be more resistant to abrasion damage than those devoid of fringes. When these fringes are absent, the *Nummulites* tests remain easily reworked and might be more easily fragmented under high-energy conditions. The formation of nummulithoclasts is probably inherited from the original texture of the *Nummulites* tests which contribute to produce silt-sized fragments (present-day hyaline tests include crystallites and needles, or large crystals with cleavages around the pores, which are present to a great proportion in the mud fraction of carbonate sediments of New Caledonia and Polynesia), and from the microporous architecture of the wall.

The production of nummulithoclasts appears dominant in Tunisia (El Garia Formation) during the Early Eocene (Late Ypresian). The resulting fragments are either integrated within the shallow nummulite-rich facies or winnowed and exported toward the distal part of the carbonate platform. At Kesra Plateau, 15-m thick *Nummulites* rudstones pass

Fig. 8 *Nummulites* of different sizes may have the same hydrodynamic behaviour depending on their density. They will be gathered by current action and will form a heterometric grain assemblage



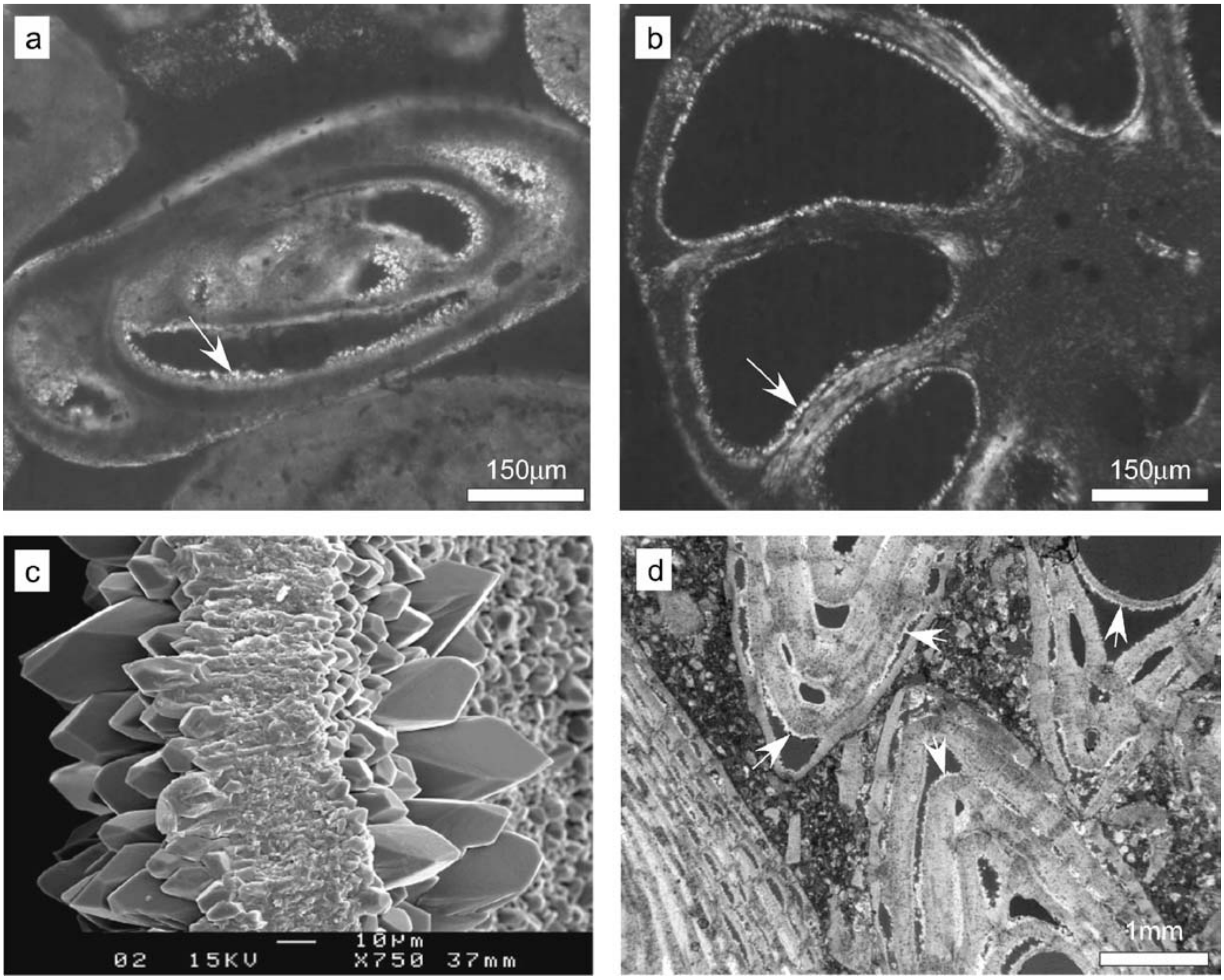
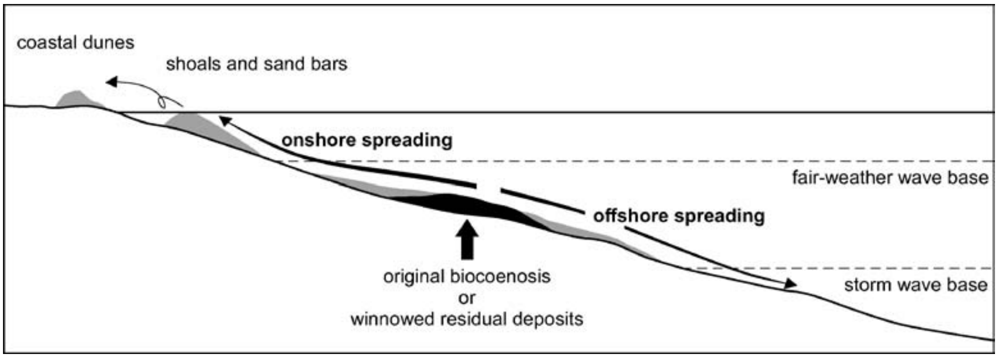


Fig. 9 Predepositional fringes of marine cement (*white arrows*) in present-day foraminifera collected in loose surface sediments and compared with those observed in fossil *Nummulites*. **a** *Quinqueloculina* sp., Holocene washover deposit from the laguna of Zarzis, Tunisia. **b** *Ammonia* sp., Holocene loose surface sediment from the laguna of Zarzis (2 m of water depth), Tunisia. **c** *Nummulites gizehensis*, Middle Eocene of Libya (NE Cyrenaica). **d** *Nummulites* sp., Lower Eocene of central Tunisia (Kesra Plateau)

Fig. 10 Synthetic facies model showing the diversity of *Nummulites* palaeoenvironments according to transport by currents



laterally to 40-m-thick nummulithoclastic packstones over a distance of 2 km. Similar observation done in Djebel Ousselat demonstrates that if the carbonate production is more important in shallow water, a significant amount of fine particles are exported down dip of the slope, and *Nummulites* grainstones accumulation may only represent stacked, condensed layers, washed of their fine content (Hasler 2004). In other localities such as Libya or Spain, the nummulithoclast production is negligible or absent during the Early to Middle Eocene (Late Ypresian to Priabonian).

Diversity of the depositional models

The peculiar hydrodynamic behaviour of *Nummulites* explains the diversity of the depositional models. In comparison with the modern living LBF, we demonstrate that *Nummulites* tests had very low apparent densities because the chamber space was probably filled with seawater and/or gas. Considering typical sedimentary processes occurring on a carbonate platform, these tests can be transported landward or seaward by weak wave-driven currents far from their original biotope (Fig. 10). Based on our observations in central Tunisia and NE Libya, reworked facies can be accumulated as subtidal or shoreline deposits characterised by local emersions (Jorry et al. 2003b). Large-microspheric *Nummulites* forming barrier-beach and lagoon-enclosing spit deposits in Pakistan have been reported by Wells (1986), and small-macrospheric *Nummulites* accumulations in the Eocene series from northern Cyrenaica have been interpreted as supratidal deposits by Jorry (2004).

These different types of skeletal accumulations are characterised by the specific shape of sedimentary bodies and primary petrophysical properties, implying variable reservoir qualities. The morphologies of these LBF accumulations are often related to the palaeotopography and to relative sea-level fluctuation; observations from the Sidi El Itayem field (onshore Tunisia) show that small lenticular sedimentary bodies are developed during highstands on the top of the palaeo-shoal when the LBF biotope, and therefore the carbonate factory, is restricted to the top of the structure. Lowstand periods, by contrast, imply a wider photic zone, and therefore a larger habitat for *Nummulites*, thus contributing to the edification of wider and more or less barkanoid coarse grain bodies (Hasler and Davaud 2001).

In terms of post-depositional processes, shallower deposits are susceptible to being preferentially affected by early diagenetic processes, leading to a reduction or an increase of the porosity. In central Tunisia and NE Libya, *Nummulites* deposited in evaporitic zones are affected by dolomitisation and dissolution processes, which significantly contribute to increase the porosity (molds and intercrystalline pores) and the permeability. Coastal dunes are only cemented by meniscus cements (vadose diagenesis) and have good porosities and permeabilities (Jorry 2004). Shoals and sand bars are characterised by a marine phreatic cementation, leading to well-cemented facies, and, therefore, are highly porous if the intranummulite porosity is preserved. The more distal *Nummulites* accumulations, i.e., the *Nummulites* banks, are generally floatstones, the porosity being dominated by primary intranummulite pores and vugs. The preservation of the porosity is furthered by the presence of early cementation in foraminiferal chambers, which contributes to preserve tests from fragmentation but decreases permeability.

Conclusions

Eocene *Nummulites* accumulations have no counterparts in present-day seas. Several depositional models have been proposed and most of them consider these bioaccumulations as the in situ record of prolific biocoenoses developed in a mid-ramp setting. The scarcity of high-energy sedimentary structures has contributed to support an autochthonous origin.

Image analysis of thin sections and SEM views indicates that the intraskeletal porosity of *Nummulites* varies from 47.5 to 62.9%. Their apparent density ranges from 1.7 to 1.9 g/cm^3 when the porous network is filled with seawater, and may range from 1.1 to 1.4 g/cm^3 in the case of infilling via gases.

Experimental measurements show that the high amount of porosity and the low density of *Nummulites* makes them easily transportable by weak currents. Moreover, bottom currents can move tests which have the same hydrodynamic behaviour but not necessarily the same size, thereby inducing the deposition of heterometric assemblages. The presence of such assemblages may explain the rarity of high-energy sedimentary structures in the *Nummulites* accumulations, the detection of which relies on the presence of subtle granulometric contrasts. In such cases, bioturbations are not necessarily needed to explain the absence of sedimentary structures.

The mechanical erosion of *Nummulites* tests in high-energy environments may be favoured by biological activity such as partial dissolution in predator guts and by bioerosion via boring organisms. The bimodal characteristic of *Nummulites* deposits—with almost only entire *Nummulites* and silt-sized nummulithoclastic particles without intermediate grains—may be explained by the early precipitation of cement within the *Nummulites* chambers that could significantly increase the rigidity of the shell (more resistant to abrasion damage) and favour the preservation of complete tests in the fossil record. When these fringes are absent, the *Nummulites* tests remain easily reworked and might be more easily fragmented during high-energy events or by bioturbating organisms.

The peculiar hydrodynamic behaviour of *Nummulites* tests can explain the diversity of the depositional models. Bottom and wave currents may induce the formation of in situ winnowed bioaccumulations or newly deposited facies by offshore or onshore spreading far from the original biocoenosis. These depositional processes determine the volume (thickness and aerial distribution) and the primary porosity and permeability of the *Nummulites* accumulations that, in turn, may influence the diagenetic processes and, consequently control the final petrophysical properties of the *Nummulites* reservoir bodies.

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