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Hydrodynamic behaviour of *Nummulites*: implications for depositional models

Stéphan J. Jorry[1], Claude-Alain Hasler[2] and Eric Davaud[1]

[1] Department of Geology, University of Geneva,13 rue des Maraˆıchers, 1205 Geneva, Switzerland
[2] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

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

1. Introduction

Nummulites accumulations occur in Late Paleocene to Early Oligocene carbonate deposits, which represent about 30 Ma in the geological record. During this time, the marine microfauna was 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 sea waters that induced nutrient deficiencies (Hallock, 1985). This is supported by a major episode of global warming expressed by a 1.5 $^{0}/_{00}$ decrease in $\delta^{18}O$ which peaked during the Early Eocene Climatic Optimum (EECO) at 52-50Ma (Kenneth and Scott, 1991; Zachos *et al.*, 2001).

Nowadays, the *Nummulites* limestones, which are extended from the West Pacific, Central Mediterranean, to the Atlantic (Figure 1), form important hydrocarbon reservoirs in northern African 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, Jorry *et al.*, 2003b; 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, 2001b; 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 the *Nummulites* a very good example of taphonomic feedback on 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; Jorry *et al.*, 2003b; 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 intraskeletal porosity, apparent density, and settling velocities of *Nummulites*, and to compare these results with those of previous 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, 5- to propose an additional hypothesis regarding the preservation of complete *Nummulites* and the associated fragmentation processes, which lead to consequent nummulithoclast production.

2. 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; Hohenegger *et al.*, 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 day carbonate systems: 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, as identified by Leutenegger (1984) on the living *Palaeonummulites venosus*.

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). Excepted for *Cycloclypeus carpentieri* whose the maximum observed diameter is 120 mm (Hohenegger *et al.*, 2000), the gigantism which characterises Eocene *Nummulites* has no counterpart in present-day protist groups. 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 shelters 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 but 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 on 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; Hallock, 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, or they are even considered as 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 formed in moderately low-energy environments between fair-weather and storm wave base. More recently, *Nummulites* have been recognized to 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) they may represent 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 encrusted 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 sea grass leaves, the second possibility being 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 Rozloznik (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. But 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 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 gives a detailed discussion on depth coenoclines and environmental considerations regarding LBF from the Western Pacific.

3. Diversity of depositional models in the fossil record

Several depositional models have been proposed to characterize the nummulite-rich accumulations (Figure 2). In most of these case studies, the deposition of *Nummulites* sediment is located around palaeoreliefs (sedimentary or structural highs) or along homoclinal carbonate ramps. Different palaeo-depths are envisaged, from 10 to 60 m depth, and different depositional relief 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 characterized by a mono-specific association of *Nummulites*, separates 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, gentle 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 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 (Juggurta 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 model has been proposed for the Ager Formation in the south Pyrenees foreland basin (Spain).

Depending on the model, *Nummulites*-rich sediments are considered as 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 Yordonava, 2001a). However, the hydrodynamic behaviour of modern benthic foraminifera has received a little 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 the 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 confers 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 explained by 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 later easily picked up 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 of the nature of the fluid that filled 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 been already suggested by several authors (Wells, 1984; Wells, 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 (unpublished data), who found threshold velocities ranging from 18 to 77 cm/s. More recently, Racey (2001) mentions an internal report of British Gas in which critical shear velocities have been 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 evidences concerning the hydrodynamic behaviour of *Nummulites* which could explain the diversity of the depositional environments in the fossil record.

4. Methodology

This work is based on the observations made on samples from outcrops and subsurface which include 1200 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 characterize 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 mm to 32 mm of diameter, types (micro- and megalo-spherical) and characterized by minimum diagenetic modifications and well-preserved intraskeletal porosity. Shape parameters (longest, intermediate and shortest orthogonal axis of the test) and apparent density (weight divided by external volume) were measured on these specimens. The settling velocities have been measured on a distance of 1.50 m, in a transparent plastic tube of 40 cm diameter, and the water salinity has been adjusted at 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 at 10°C, 20°C and 26,5°C. The measures were repeated alternatively on «full-water» (water injection) and «full-air» (air drying) *Nummulites*.

Finally, theoretical settling velocities have been 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 have developed much larger size.

5. Results

5.1. Porosity and apparent density measurements

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

These micropores was detected by Carpenter (1850) and confirmed by Schaub (1981) who described perforations in the walls of *Nummulites* (Figure 3a). The role of these microstructures is not explained for 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 be 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 has been achieved by image analyses on 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 (Figure 3b-d). It ranges from 25 to 36% of the wall volume. The porosity of chambers, estimated by image analysis on successive microtomographic sections and by point counting on thin sections, ranges from 30 to 42% (Figure 4). As consequence, the total porosity of *Nummulites* varies from 47.5 to 62.9%. These results are very similar to those obtained on living foraminifera; porosity measurements on *Amphisorus* are as high as 72% (Aigner, 1982).

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 hyalin tests are mainly composed of low magnesium calcite (LMC), according to our measurements on *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}), following this equation:

$$\rho_s = (1-\varphi) \cdot \rho_{LMC} + \varphi \cdot \rho_{fluid}$$

As after the cell's death, chambers may be filled in by seawater or by gas (produced by the decay of organic material), two functions can be adjusted (Figure 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 in with seawater. Infilling gases induced a drastic fall of the apparent densities (1.1 to 1.4 g/cm^3). These low values suggest that *Nummulites* tests can be transported as 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).

5.2. 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 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 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 intraskeletal porosity partly preserved, have been 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} (Figure 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 (Figure 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:

$$U^*_c = 1.959 + 0.253\sqrt{\beta \cdot g\left(\frac{\sqrt[3]{D_i \cdot D_l \cdot D_s}}{1.32}\right) \cdot \frac{(\rho_s - \rho_f)}{\rho_f}}$$

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

$$\beta = -0.0717 \cdot log_{10}(W_d) + 0.0625 \qquad for\ W_d < 2.5$$

$$\beta = 0.029 + 0.003 \cdot W_d - 9.935 \cdot 10^{-5} \cdot W_d^2 \qquad for\ W_d > 2.5$$

$$W_d = -0.375 + 0.29 \cdot D_d - 0.002 \cdot D_d^2 + 4.731 \cdot 10^{-6} \cdot D_d^3 \qquad for\ D_d < 134.9$$

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

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/sec]) and to the gravity constant (g [cm/sec^2]):

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

The obtained threshold shear velocities confirm that pluricentimetre-scale *Nummulites* can easily be moved by wave-driven currents (Figure 7a). Large B-forms *Nummulites* (2 cm in diameter) with an apparent density of 1.8 g/cm^3 are transported when the shear velocity reaches 3.3 cm/s (Figure 5 and Figure 7a). These values are is about the half of those proposed by Racey (2001), who used a flume tank measurements. 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 deep, which suggests a large range of possible depositional environments (Figure 7b). If chambers are filled in with gas, the potential reworking depth falls down to 60 m deep (Figure 5 and Figure 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 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 chambers (seawater or gas).

6. Discussion : implications in depositional processes

6.1. 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 has been 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 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, which could be created by the presence of a physical barrier or by the presence of dense sea-grass 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 up internal porosity, and on the degree of early intraskeletal cementation (Figure 8). Consequently, *Nummulites* of different size 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 in quartz or argillaceous particles which may form drapes emphasizing 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, 2003b, 2004).

6.2. Preservation and fragmentation of *Nummulites* tests

The *Nummulites* carbonate production is often 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 depend on the distance of transportation. Severin and Lipps (1987) clearly demonstate that living *Alveolinella quoyi* tests are relatively resistant to damage by abrasion. Beavington-Penney

(2004) shows that it is impossible to reproduce on *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 1000 hours 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 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 (Hickmann and Lipps, 1983), and by bioerosion by boring algae, fungi and sponges (Kloos, 1982). In present-day dead benthic foraminifers that we collected in loose superficial sediment, fringes of early marine cements are also frequently observed (Figure 9a, 9b). 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 (Figure 9c, 9d). The pre-depositional character of this cement for the Eocene *Nummulites* is attested by its absence in interparticle pore spaces (Figure 9d). This early precipitation of cement within internal structures of *Nummulites* slightly increase 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-size fragments (present-day hyaline tests include crystallites and needles, or large crystals with cleavages around the pores, which are present in great proportion in the mud fraction of carbonate sediments of New Caledonia and Polynesia) and from 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 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 the slope, and *Nummulites* grainstones accumulation may only represent stacked condensed layers, washed out of their fine content (Hasler, 2004). In other localities, such as Libya or Spain, the nummulithoclast production is negligible or absent during Early to Middle Eocene (Late Ypresian to Priabonian).

6.3. 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 (Figure 10). Based on our observations in Central Tunisia and NE Libya, reworked facies can be accumulated as subtidal or shoreline deposits, characterized by local emersions (Jorry *et al.*, 2003b). Large-microspheric *Nummulites* forming barrier-beach and lagoon-enclosing spit deposits in Pakistan has 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 characterized by 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 term of post-depositional processes, shallower deposits are susceptible to be preferentially affected by early diagenetic processes, which leads to reduce or increase the porosity. In Central Tunisia and NE Libya, *Nummulites* deposited in evaporitic zones are affected by dolomitization 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 characterized by a marine phreatic cementation, leading to well-cemented facies, therefore 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 contribute to preserve tests from fragmentation but decreases permeability.

7. 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 on thin sections and SEM views indicate 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 in with seawater, and may range from 1.1 to 1.4 g/cm^3 in the case of gases infilling.

Experimental measurements show that the high amount of porosity and the low density of *Nummulites* make them easily transportable by weak currents. Moreover, bottom currents can move tests which have the same hydrodynamic behaviour but not necessarily the same size, 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 by boring organisms. The bimodal characteristic of *Nummulites* deposits - with almost only entire *Nummulite*s 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 to 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 form 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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References

Aigner T (1982) Event stratification in nummulite accumulations and shell beds from the Eocene of Egypt. In: Einsele G, Seilacher A (eds) Cyclic event stratification, Springer Verlag, Berlin, pp 248–262

Aigner T (1983) Facies and origin of nummulitic build-ups: an example from the Giza Pyramids Plateau (Middle Eocene, Egypt). Neues Jahrbuch Geol Palaontol Abh 166:347–368

Aigner T (1985) Biofabrics as dynamic indicators in nummulite accumulations. J Sediment Petrol 55:131–134

Alve E, Olsgard JM (1999) Benthic foraminifera colonization in experiments with copper-contaminated sediments. J Foram Res 29:186–195

Anketell JM, Mriheel, IY (2000) Depositional environment and diagenesis of the Eocene Jdeir Formation, Gabes-Tripoli Basin, western offshore Libya. J Petrol Geol 23:425–447

Arni P (1965) L'évolution des Nummulitinae en tant que facteur de modification des dépôts littoraux. Mém BRGM 32:7–20

Bailey HW, Dungworth G, Hardy M, Scull D, Vaughan RD, (1989) A Fresh Approach of the Metlaoui. Actes des II^emes^ Journées de Géologie Tunisienne appliquée à la recherche des Hydrocarbures:281–307

Bartholdy J (2002) The architecture of *Nummulites* (Foraminifera), re-examined. PhD Dissertation, Frei Universität Berlin, 98 pp

Beavington-Penney SJ (2004) Analysis of the effects of abrasion on the test of *Palaeonummulites venosus*: implications for the origin of nummulithoclastic sediments. Palaios 19:143–155

Beavington-Penney SJ, Racey A (2004) Ecology of extant nummulitids and other large benthic foraminifera: applications in palaeoenvironmental analysis. Earth-Sci Rev 67:219–265

Bernasconi A, Poliani G, Dakshe A (1991) Sedimentology, petrography and diagenesis of Metlaoui Group in the offshore Northwest of Tripoli. In: Salem MJ, Belaid MN (eds) Geology of Libya, Earth Science Society of Libya, Tripoli, pp 1907–1928

Bernhard JM (1988) Postmosterm vital staining in benthic foraminifera: duration and importance in population and distributional studies. J Foram Res 18:143–146

Bishop WF (1985) Eocene and Upper Cretaceous carbonate reservoirs in East Central Tunisia. Oil Gas J Dec 2:137–142

Blanc-Vernet L, Clairefond P, Orsolini P (1979) Les Foraminifères. In: Burollet PF, Clairefond P, Winnock E (eds) La mer pélagienne - étude sédimentologique et écologique du Plateau tunisien et du Golfe de Gabès, Géol Méd 6, pp 171–209

Blondeau A (1972) Les Nummulites. Vuibert, Paris, 254 pp

Bolton TF, Havenhand JN (1997) Physiological versus viscosity-induced effects of water temperature on the swimming and sinking velocity of larvae of the serpulid polychaete Galeolaria caespitosa. Mar Ecol Progress Series 159:209–218

Caline B, Ben-Ahmad M, Klitzsch M, Zuckmeyer E, Charpentier P (2003) A new insight into reservoir distribution in a carbonate nummulite platform from integration of recent core data and 3D seismic (El Gueria Fm, concession 137N, NW offshore Libya). In: Salem MJ, Oun KM (eds) The geology of northwest Libya II, Earth Science Society of Libya, Tripoli, pp 261–280

Carpenter WB (1850) On the Microscopic Structure of *Nummulina*, *Orbitolites*, and *Orbitoides*. Quaterly J Geol Soc London 6:21–38

Chapman F, Jones TR (1986) Report on the microzoa in marl and silts form Barry Dock, near Cardiff. Quat J Geol Soc London 52:485–488

Comte D, Lehman P (1974) Sur les carbonates de l'Yprésien et du Lutétien basal de la Tunisie Centrale. Compagnie Française des Pétroles, Notes et Mém 11:225–292

Cowen R (1983) Algal symbiosis and its recognition in the fossil record. In: Tevesz MJS, McGall PL (eds) Biotic interactions in recent and fossil benthic communities, Plenum, New York, pp 432–478

Davaud E, Septfontaine M (1995) Post-mortem onshore transportation of epiphytic foraminifera: recent example from the tunisian coastline. J Sediment Res 65:136–142

Davies GR (1970) Carbonate bank sedimentation, eastern Shark Bay, Western Australia. Am Assoc Petrol Geol 13:85–168

Debenay JP, André JP, Lesourd M (1999) Production of lime mud by breakdown of foraminiferal tests. Mar Geol 157:159–170

Deeke W (1914) Paleontologische Betrachtungen. Neues Jahrb. Mineral, Geol Paläontol:1

Eichenseer H, Luterbacher H (1992) The marine Paleogene of the Tremp region (NE Spain): depositional sequences, facies history, biostratigraphy and controlling factors. Facies 27:119–152

Fournié D (1975) L'analyse séquentielle et la sédimentologie de l'Yprésien de Tunisie. Bull Cent Rech Pau-SNPA 9:27–75

Fütterer E (1982) Experiments on the distribution between wave and current influenced shell accumulations. In: Einsele G, Seilacher A (eds) Cyclic event stratification, Springer Verlag, Berlin, pp 175–179

Ginsburg RN (2005) Disobedient sediments can feedback on their transportation, deposition and geomorphology. Sediment Geol 175:9–18

Hallock P (1979) Trends in test shape with depth in large, symbiont-bearing foraminifera. J Foram Res 9:61–69

Hallock P (1981) Light dependence in *Amphistegina*. J Foram Res 11:40–46

Hallock P (1985) Future farmer of the sea. Nat Hist 94:60–67

Hallock P, Forward LB, Hansen HJ (1986) Influence of environment on the test shape of *Amphistegina*. J Foram Res 16:224–231

Hallock P, Rottger R, Wetmore K (1991) Hypotheses on form and function in foraminifera. In: Lee JJ, Anderson OR (eds) Biology of foraminifera, Academic Press, Cambridge, pp 41–66

Hannah F, Rogerson A (1997) The temporal and spatial distribution of foraminiferans in marine benthic sediments of the Clyde Sea area, Scotland. Estuar Coast Shelf Sci 44:377–383

Hasler CA (2004) Geometry and internal discontinuities of an Ypresian carbonate reservoir (SIT Field, Tunisia). PhD Thesis, Université de Genève, Terre Environ 45, 230 pp

Hasler CA, Davaud E (2001) External geometry of nummulite accumulations within a sequence stratigraphy framework, Sidi El Itayem field, Ypresian, Tunisia. Géol Méd 28:89–92

Hickman CS, Lipps JH (1983) Foraminiferivory: Selective ingestion of foraminifera and test alterations produced by the neogastropod *Olivella*. J Foram Res 12:108–114

Hohenegger J (2004) Depth coenoclines and environmental considerations of Western Pacific larger foraminifera. J Sed Res 34:9–33

Hohenegger J (2005) Estimation of environmental paleogradient values based on presence/absence data: a case study using benthic foraminifera for paleodepth estimation. Palaeogeogr Palaeoclimatol Palaeoecol 217:115–130

Hohenegger J, Yordanova E (2001a) Displacement of larger foraminifera at the western slope of Motobu peninsula (Okinawa, Japan). Palaios 16:53–72

Hohenegger J, Yordanova E (2001b) Depth-transport functions and ersion-deposition diagrams as indicators of slope inclination and time-averaged traction forces: applications in tropical reef environments. Sedimentology 48:1025–1046

Hohenegger J, Yordanova E, Hatta A (2000) Remarks on West Pacific Nummulitidae (Foraminifera). J Foram Res 30:3–28

Hohenegger J, Yordanova EK, Nakano Y, Tatzreiter F (1999) Habitats of larger Foraminifera on the upper reef slope of Sesoko Island, Okinawa, Japan. Mar Micropal 36:109–168

Hottinger L (1973) Distribution of larger Peneroplidae, Borelis and Nummulitidae in the Gulf of Elat, Red Sea. Utrecht Micropal Bull 15:35–110

Hottinger L (2000) Functional morphology of benthic foraminiferal shells, envelopes of cells beyond measures. Micropaleontology 46:1–12

Jorry SJ, Ben-Ahmad M, Cantaloube S (2003a) Facies distribution and geometry of the El Gueria Formation in concession 137N - Preliminary results of a field analogue study from Kesra Plateau. In: Salem MJ, Oun KM (eds) The geology of northwest Libya II, Earth Science Society of Libya, Tripoli, pp 99–105

Jorry SJ, Davaud E, Caline B (2003b) Structurally controlled distribution of nummulite deposits: example of the Ypresian El Garia Formation (Kesra Plateau, Central Tunisia). J Petrol Geol 23:283–306

Jorry SJ (2004) The Eocene *Nummulites* carbonates (Central Tunisia and NE Libya): sedimentology, depositional environments, and application to oil reservoirs. PhD Thesis, Université de Genève, Terre & Environ 48, 226 pp

Kenneth JP, Scott LD (1991) Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Paleocene. Nature 353:225–229

Kidwell SM, Jablonski D (1983) Taphonomic feedback. In: Tevesz MJS, McCall PL (eds) Biotic interactions in recent and fossil benthic communities, Plenum Press, New York, pp 195–253

Kloos DP (1982) Destruction of tests of the foraminifer *Sorites orbiculus* by endolithic microorganisms in a lagoon on Curaçao (Netherlands Antilles). Geol. Mijnbouw 61:201–205

Kotler E, Martin RE, Liddell WD (1992) Experimental analysis of abrasion and dissolution resistance of modern reef-dwelling foraminifera: implications for the preservation of biogenic carbonate. Palaios 7:244–276

Krüger R (1994) Untersuchungen zur Entwicklung rezenter Nummulitiden: *Heterostegina depressa*, *Nummulites venosus* und *Cycloclypeus carpenteri*. PhD Thesis, University of Kiel, Hochschulschriften, 70, 97 pp

Kulka A (1985) Arni sedimentological model in the Tatra Eocene. Kwart Geol 29,1:31-64

Langer MR, Hottinger L (2000) Biogeography of selected "larger" foraminifera. Micropaleontolgy 46:105–126

Larsen AR (1976) Studies of recent *Amphistegina*: taxonomy and some ecological aspects. Israel J Earth-Sci 25:1–26

Larsen AR, Drooger CW (1977) Relative thickness of the test in *Amphistegina* species of the Gulf of Elat. Utrecht Mircopal Bull 15:225–239

Le Roux JP (1997) An Excel program for computing the dynamic properties of particles in Newtonian fluids. Comp Geosci 23:671–675

Leutenegger S (1984) Symbiosis in benthic foraminifera: specificity and host adaptations. J Foram Res 14:16–35

Leutenegger S, Hansen HJ (1979) Ultrastructure and radiotracer studies of pore function in Foraminifera. Mar Bio 54:11–16

Loucks RG, Moody RTJ, Bellis JK, Brown AA (1998) Regional depositional setting and pore network systems of the El Garia Formation (Metlaoui Group, Lower Eocene), offshore Tunisia. In: Macgregor DS, Moody RTJ, Clark-Lowes DD (eds) Petroleum geology of north Africa, Geol Soc Sp Pub 132, pp 355–374

Madsen OS (1994) Spectral wave-current bottom boundary layer flows. Proceedings, 24th International Conference, Coast Engin Res Council/ASCE:384–398

Martin RE, Liddell WD (1991) Taphonomy of foraminifera in modern carbonate environments. In: Donovan SK (ed) The processes of fossilization. Belahven Press, London, pp 170–193

Moody RTJ (1987) The Ypresian carbonates of Tunisia - a model of foraminiferal facies distribution. In: Hart MB (ed) Micropalaeontology of carbonate environments. BMS Series, Ellis Horwood, Chichester, pp 82–92

Moody RTJ, Grant GG (1989) On the importance of bioclasts in the definition of depositional model for the Metlaoui carbonate group. Actes des II^{ème} Journées de Géologie Tunisienne Appliquée à la Recherche des Hydrocarbures, Mém Etap 3:409–427

Moody RTJ, Loucks RG, Brown AA, Sandman I (2001) Nummulite deposits of the Pelagian area - depositional models and diagenesis. North Africa Research Workshop, 4th-5th September 2001, abstract

Murray JW (1987) Biogenic indicators of suspended sediment transport in marginal marine environments: quantitative examples from SW Britain. J Geol Soc 144:127–133

Murray JW, Bowser SS (2000) Mortality, protoplasm decay rate, and reliability of staining techniques to recognize “living foraminifera”: a review. J Foram Res 30:66–70

Murray JW, Sturrock S, Weston JF (1982) Suspended load transport of foraminiferal tests in a tide and wave swept sea. J Foram Res 12:51–65

Nemkov GI (1962) Remarques sur la paléoécologie des Nummulites. Vopr Micropaleontol, SSSR 6:64–72, Trad BRGM

Poizat C (1970) Hydrodynamisme et sédimentation dans le golfe de Gabès (Tunisie). Tethys 2,1:267–296

Pecheux MJF (1995) Ecomorphology of a recent large foraminifer, *Operculina ammonoides*. Geobios 28:529–566

Racey A (2001) A review of Eocene nummulite accumulations: structure, formation and reservoir potential. J Petrol Geol 24:79–100

Racey A, Bailey HW, Beckett D, Gallagher T, Hampton MJ, Mc Quilken J (2001) The petroleum geology of the Early Eocene El Garia Formation, Hasdrubal field, offshore Tunisia. J Petrol Geol 24:29–53

Renema W (2005) Depth estimation using diameter-thickness ratios in larger benthic foraminifera. Lethaia 38:137–141

Rozlozsnik P (1927) Einleitung in das studien der Nummulinen und Assilinen. Mitt Jahr Ungar Geol Anstalt

Savarese M, Dodd JR, Lane NG (1996) Taphonomic and sedimentological implications of crinoid intraskeletal prorosity. Lethaia 29:141–156

Schaub H (1981) Nummulites et Assilines de la Téthys Paléogène ; taxinomie, phylogenèse et biostratigraphie. Mémoires suisses de Paléontologie 104, 238 pp

Severin KP, Lipps JH (1987) Taphonomy of the large, living fusiform foraminiferan *Alveolinella*: implications for the accumulation of alveolinid and fusulinid limestones. Geological Society of America, Abstract with Program 19:838

Severin KP, Lipps JH (1989) The weight-volume relationship of the test of *Alveolinella quoyi*: implications for the taphonomy of large fusiform foraminifera. Lethaia 22:1–12

Sherwood CR (2004)
http://woodshole.er.usgs.gov/staffpages/csherwood/sedx_equations/ RunWCCalcs.html

Thomas FC, Schafer, CT (1982) Distribution and transport of some common foraminiferal species in the Minas Basin, eastern Canada. J Foram Res 12:24–38

Vennin E, Van Buchem FSP, Joseph P, Gaumet F, Sonnenfeld M, Rebelle M, Fakhfakh-Ben Jemia H, Zijlstra H (2003) A 3D outcrop analogue model for Ypresian nummulitic carbonate reservoirs: Jebel Ousselat, northern Tunisia. Petrol Geosci 9:145–161

Wang P, Murray JW (1983) The use of foraminifera as indicators of tidal effects in estuarine deposits. Mar Geol 51:239–250

Wells NA (1984) Marine and continental sedimentation in the early Cenozoic Kohat Basin and adjacent northwestern Indo-Pakistan. Unpublish PhD Dissertation, Univ of Michigan, 465 pp

Wells NA (1986) Biofabrics as dynamic indicators in nummulite accumulations: discussion. J Sediment Petrogr 56:318–320

Yordanova EK, Hohenegger J (2002) Taphonomy of larger Foraminifera; relationships between living individuals and empty tests on flat reef slopes (Sesoko Island, Japan). Facies 46:29–34

Yordanova EK, Hohenegger J (2004) Morphocoenoclines of living operculinid foraminifera. Micropaleontology 50:149–177

Zachos J, Pagani M, Sloan L, Thomas E, Billups K (2001) Trends, rythms, and aberrations in global climate 65 Ma to present. Science 292:686–693

Figure captions

Table 1. Shape parameters (Dl, Di, Ds : large, intermediate, small diameter), density, settling velocity measured on *Nummulites*. Critical 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 behave like coarse sands (1.1 mm) to fine gravels (5.0 mm).

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

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

Figure 3. Internal structure of fossil *Nummulites* tests.

a: Illustration of the microporous test of *Nummulites laevigatus* (after 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.

Figure 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.

Figure 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.

Figure 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.

Figure 7a. 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*, which 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.

Figure 7b. 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 removed down to 50 m deep during storm conditions. If the intraskeletal porous network is filled with gas, they can be removed down to 60 m deep.

Figure 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 an heterometric grain assemblage.

Figure 9. Predepositional fringes of marine cement in present day foraminifera collected in loose surficial sediments and comparison with those observed in fossil *Nummulites*.

a: *Quinqueloculina ? sp.*, Holocene washover deposit from the laguna of Zarzis, Tunisia

b: *Ammonia sp.*, Holocene loose superficial 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)

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

Figure 1 - Jorry et al. 2006 - FACIES

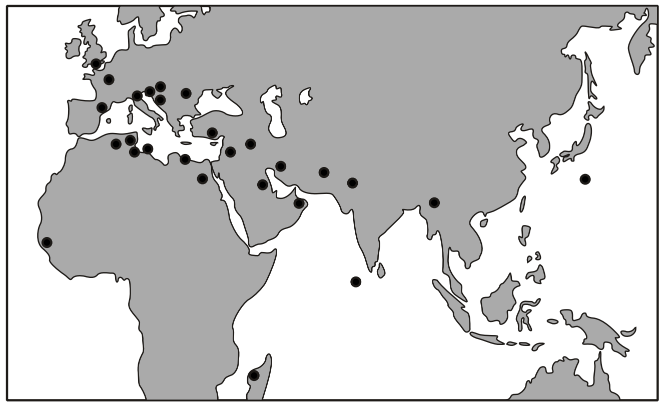
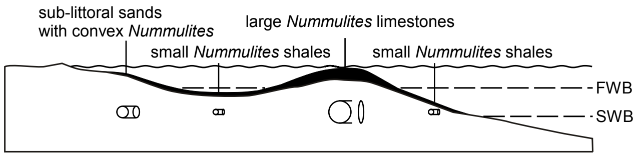


Figure 2 - Jorry et al. 2006 - FACIES

Localities	Synthetic Facies Models	Comments

Russia



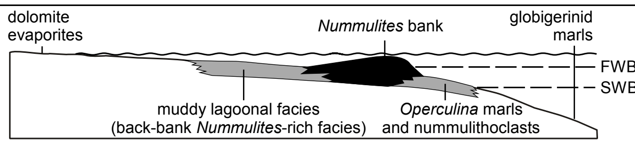
after Nemkov, 1962

(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

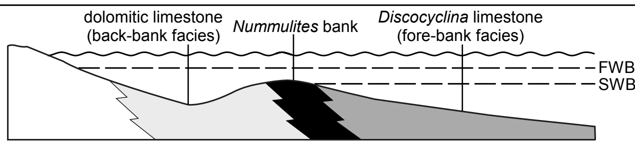


after Arni, 1965

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

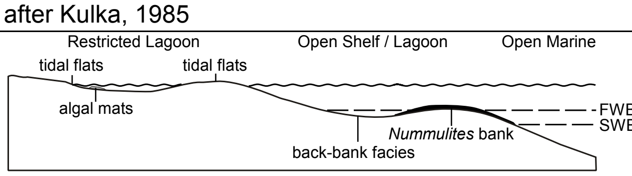


after Kulka, 1985

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

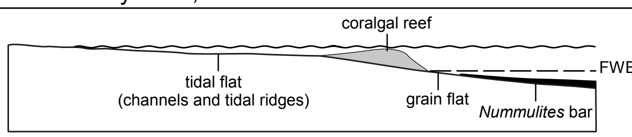


after Bailey *et al.*, 1989

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

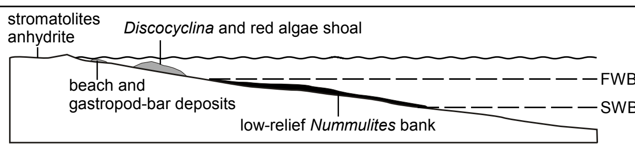


after Eichenseer and Luterbacher, 1992

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

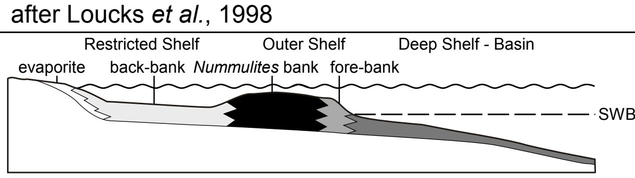


after Loucks *et al.*, 1998

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

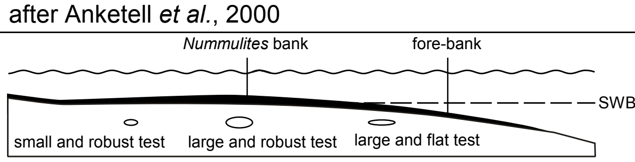


after Anketell *et al.*, 2000

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

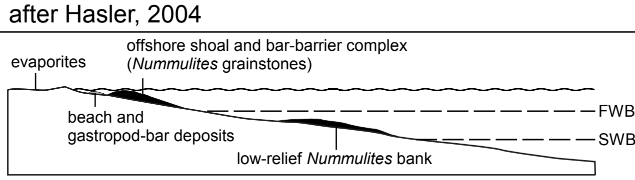


after Hasler, 2004

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

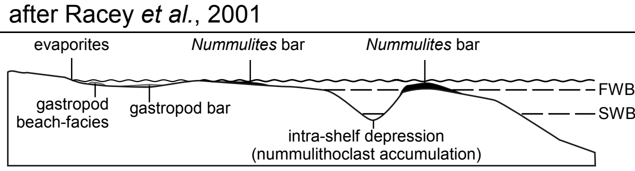


after Racey *et al.*, 2001

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.

Figure 3 - Jorry et al. 2006 - FACIES

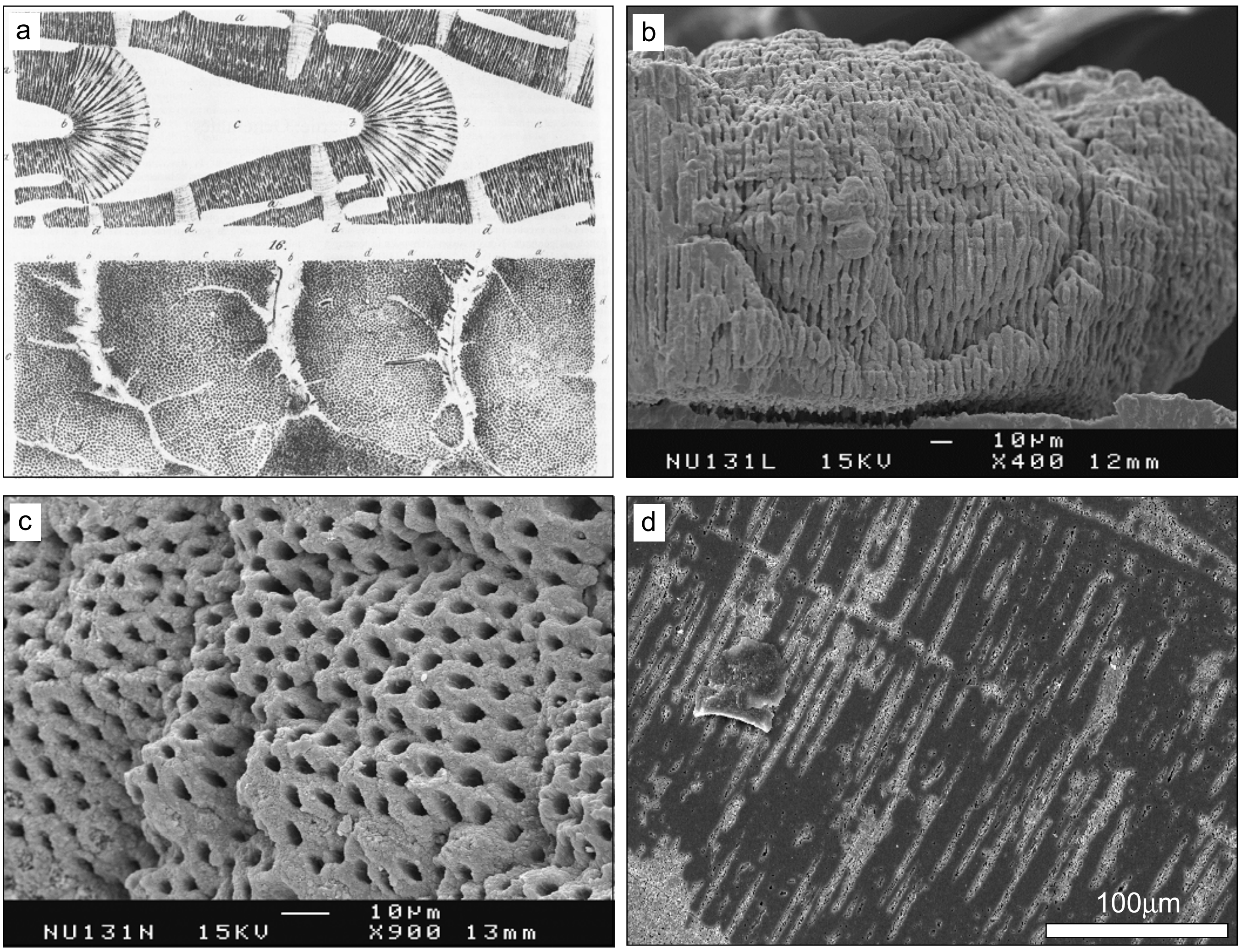
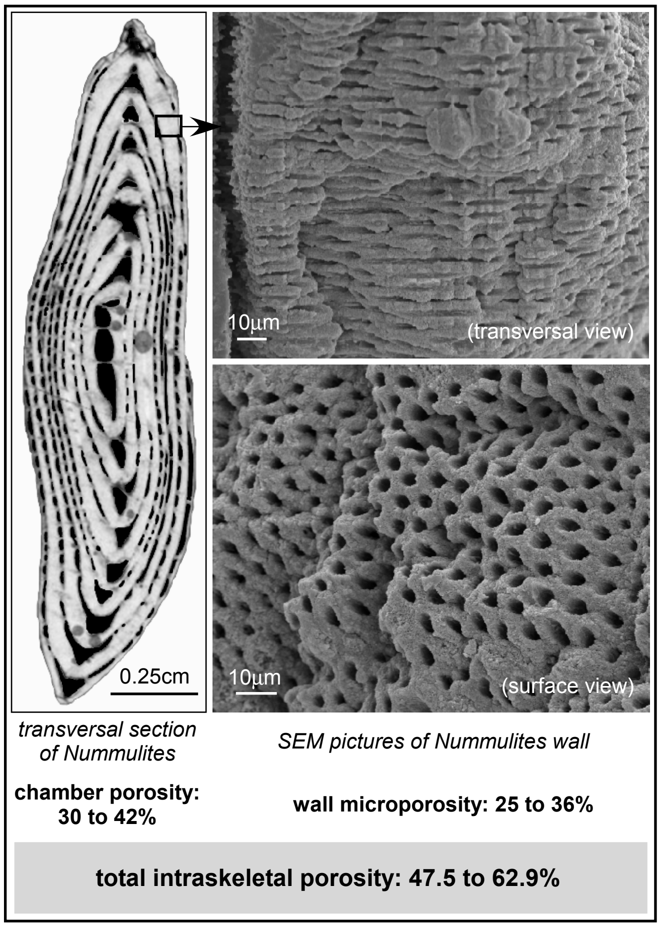


Figure 4 - Jorry et al. 2006 - FACIES



Samples	Sexual Generation	*Nummulites* shape and size parameters		*Nummulites* density	measured settling velocity	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)
		D_l D_i (mm)	D_S (mm)	ρ_s (g/cm3)	W_m (cm/s)			
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

Figure 5 - Jorry et al. 2006 - FACIES

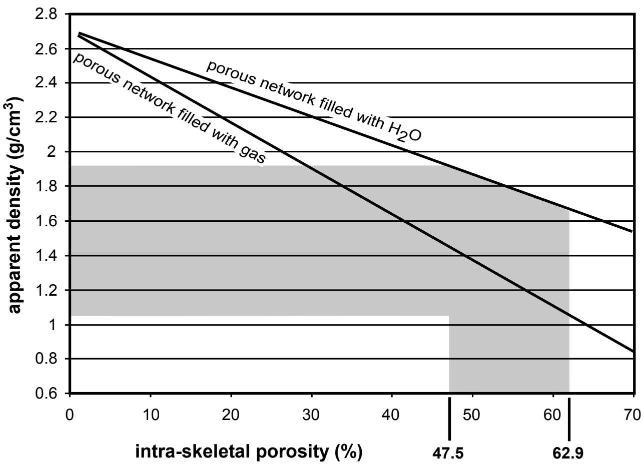


Figure 6 - Jorry et al. 2006 - FACIES

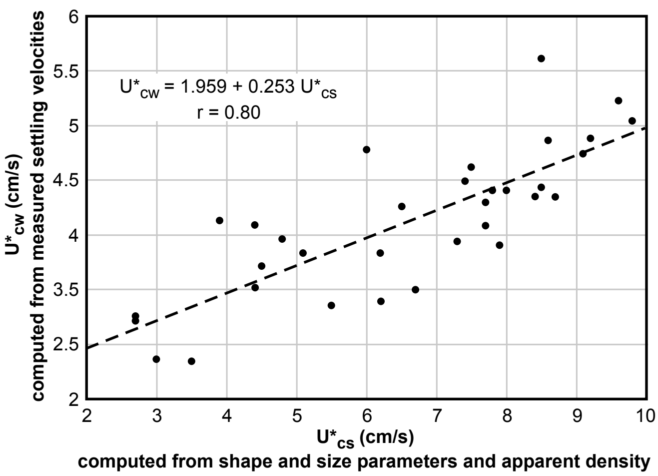


Figure 7 - Jorry et al. 2006 - FACIES

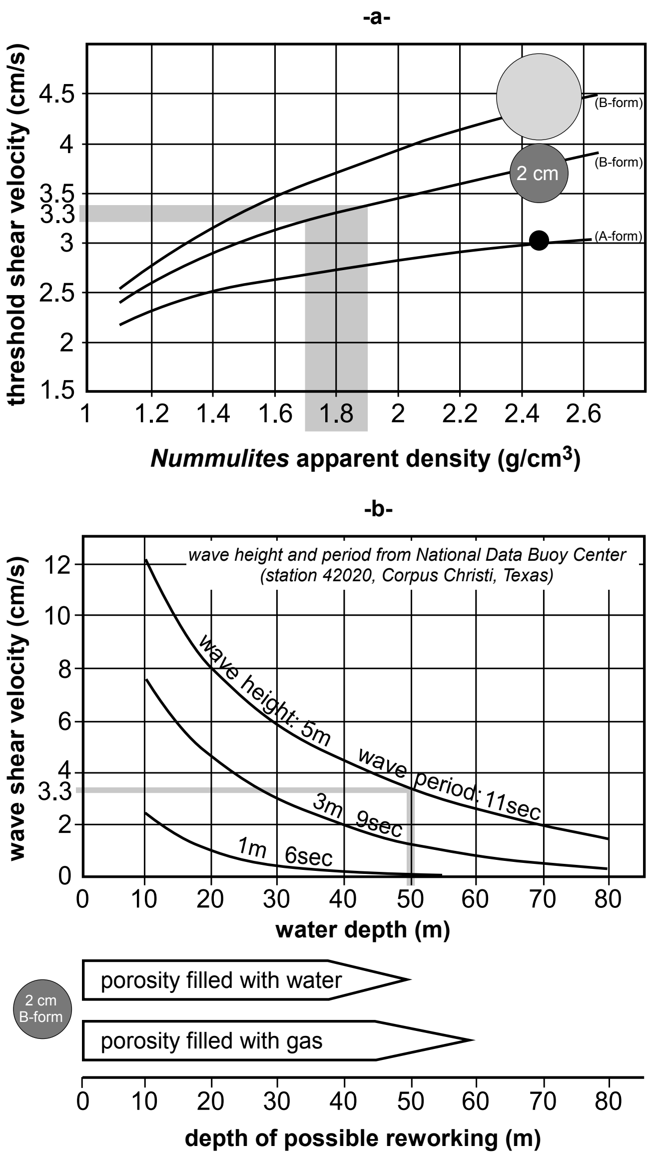


Figure 8 - Jorry et al. 2006 - FACIES

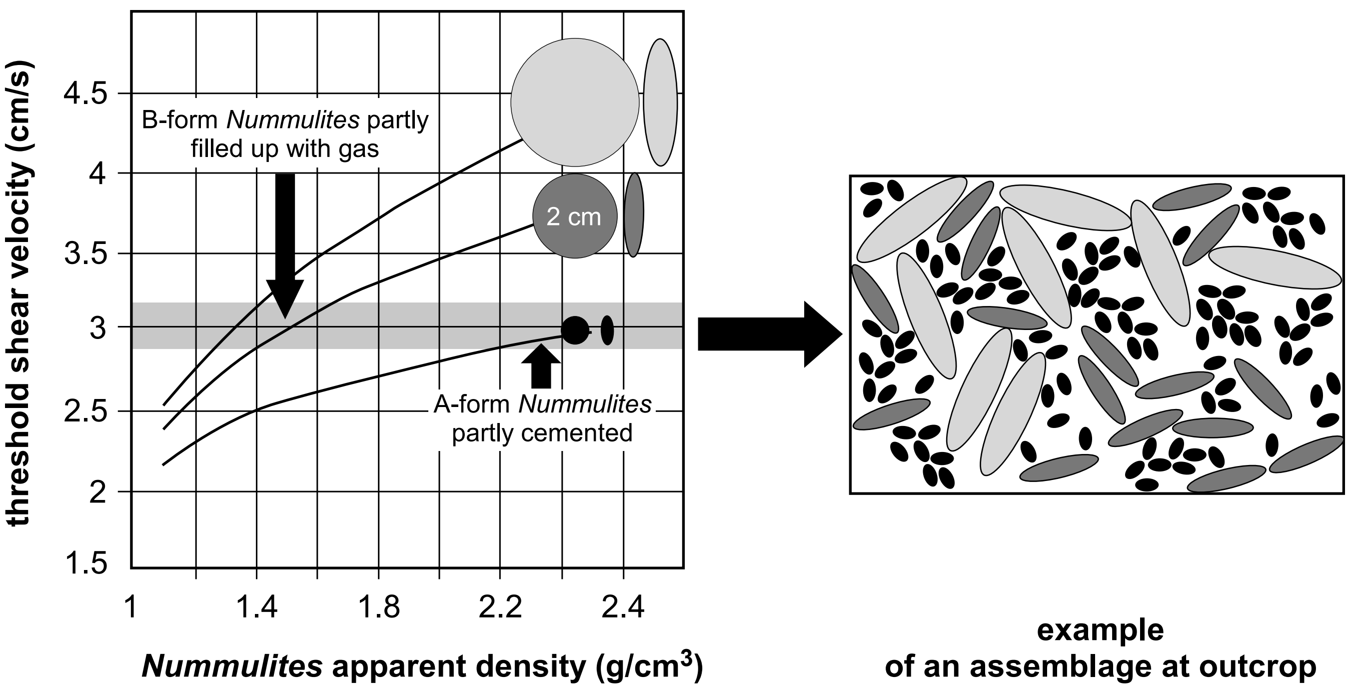


Figure 9 - Jorry et al. 2006 - FACIES

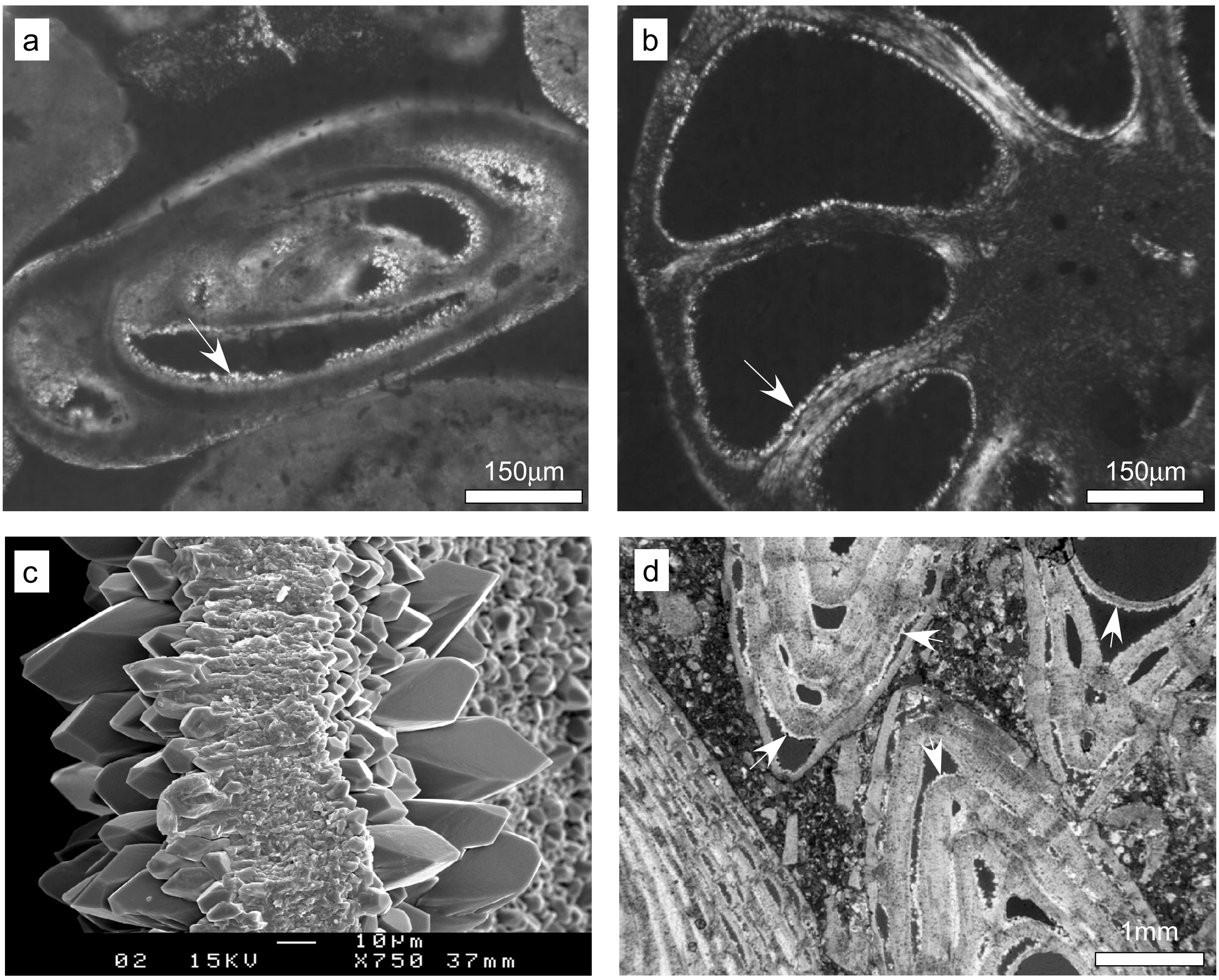


Figure 10 - Jorry et al. 2006 - FACIES