



Nummulitids hydrodynamics: an example using *Nummulites globulus* Leymerie, 1846

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ABSTRACT - The main physical variables influencing the hydrodynamic behaviour of nummulitid tests are size, density and shape. After measuring these variables, further parameters must be calculated to obtain an approximation to the hydrodynamic behaviour of the test. These parameters are volume, nominal diameter, critical shear velocity, critical shear stress, shape entropy, shape-independent settling velocity, settling velocity of a non spherical form, Reynolds number, and drag coefficient. Some of these data were calculated by combining shell measurements with physical properties of the seawater.

The aim of this paper is to explain numerical calculations for qualifying and quantifying the hydrodynamic parameters of nummulitids. Every single step or formula is important to evaluate the hydrodynamics of a particle or test respectively, especially in shallow water environments where energy strongly varies depending on different physical factors induced by the climate and the topography of the platform. Several methods to calculate the same parameters are also presented and compared to show the best-suited one for nummulitids.

In the fossil record, the faunal composition and the distribution of tests mainly depend on the two groups of cause-effect effects: in vita and post mortem. Inferences about a fossil shallow benthic fauna must consider beside biological and ecological features further physical parameters like transport and deposition leading to distinct distribution patterns.

RIASSUNTO - [Idrodinamica dei nummulitidi: l'esempio di *Nummulites globulus* Leymerie, 1846] - Lo scopo dell'articolo è di illustrare il procedimento matematico che porta ad ottenere i parametri idrodinamici che servono a valutare la risposta dei gusci, sia in vita che post mortem, ad un input energetico che ne può causare il trasporto. La quantificazione del trasporto e la sua qualificazione avviene tramite il calcolo matematico dei parametri idrodinamici del materiale trasportato: in questo caso i nummulitidi. I parametri calcolati sono, volume, diametro nominale, velocità critica tangenziale, stress critico, entropia del guscio, velocità di affondamento adimensionale, velocità di affondamento reale, numero di Reynolds e coefficiente di penetrazione. Le principali variabili fisiche che influenzano il comportamento idrodinamico di questi gusci sono la taglia, la densità e la forma. Ottenute queste misure per ogni singolo esemplare, possono quindi essere calcolati matematicamente e statisticamente altri parametri per ottenere un quadro completo dell'idrodinamica. L'esecuzione dei calcoli e la loro interpretazione danno un'immagine quantitativa e qualitativa del trasporto possibile per un dato ambiente. Sulla base dell'analisi qui riportata, lo studio delle caratteristiche idrodinamiche dei macroforaminiferi appare importante quanto lo studio delle caratteristiche biologiche ed ecologiche in un contesto di ricostruzione paleo ambientale. Soprattutto in ambienti di acqua poco profonda, dove questi organismi hanno vissuto e vivono con particolare abbondanza, lo studio dei comportamenti idrodinamici delle associazioni diventa fondamentale sia per ricostruire le distribuzioni di facies, sia per risalire alla ricostruzione delle caratteristiche fisiche dell'ambiente deposizionale.

INTRODUCTION

The shape of particles has many applications in sedimentology, including paleoenvironmental interpretation and sediment transport studies (Le Roux, 2004). Unfortunately, most works about paleoenvironmental analyses do not include the transport effect. Sand transport plays a vital role in many aspects of applied sedimentology and engineering. Sea-sand may be moved by tidal-, wind- or wave-driven currents, by waves or often by both (Soulsby, 1997). Understanding the intensity of the processes in terms of energetic input, which occur in marine environment, and understanding in which way every particle reacts to hydrodynamic parameters is partially unclear because of the high complexity. Previous studies have shown that modern larger benthic foraminifera can be easily reworked by waves and currents (Davies, 1970; Hohenegger & Yordanova, 2001a, b; Yordanova & Hohenegger, 2007) and several authors point out that the hydrodynamic behaviour of tests is an important factor controlling their

distribution in recent environment as well as in the fossil record (e.g., Jorry et al., 2006). So far, the calculated hydrodynamic behaviour of sand is in concordance with the observed values obtained in laboratory using several mathematical approximations. In the same way, concerning nummulitids, several geometrical approximations give the opportunity to compare their shape with the shape of sand grains. These results can be compared with those obtained by experimental analyses on optimally preserved tests of recent nummulitids. The parameters obtained by the theoretical and empirical approach are extremely coincident (Briguglio & Hohenegger, 2008). The aim of this paper is to propose a methodology to obtain these parameters and to extrapolate from mathematical analysis. The use of *N. globulus*, and the choice of selecting only A-forms, is just an example to demonstrate the calculation methods. The discussion of the obtained results concerning *N. globulus* is thus not the task of this paper; its aim is to show the importance of hydrodynamic parameters for paleoenvironmental reconstruction.

For the calculation of the hydrodynamic behaviour of a test, the systematic position becomes important, because the transport of a test along a slope depends on test shape, density and size, as explained above, and systematics is mainly based on morphological differences. Because of this, the distribution of objects within an environment can sometimes be compared with a species-specific distribution. Concerning foraminifera, and specially nummulitids, this parallelism between hydrodynamic features and taxonomy is not always correct. The prominent generation dimorphism in symbiont-bearing benthic foraminifera displaces generations of the same species in different environment because of their differing hydrodynamic behaviour, while species that are different in their internal structures, which could have just a small role in term of density variation, can still have the same hydrodynamic behaviour.

MATERIALS AND METHODS

The data published in this paper were taken on 19 optimally preserved tests (*sensu* Yordanova & Hohenegger, 2002) of A forms of *Nummulites globulus* Leymerie, 1846. The material originates from the Tresp basin (southern Pyrenean, Spain). Only very well preserved tests were selected because, according to Yordanova & Hohenegger (2002), optimal preservation indicates the release of the test by the protoplasm within the last two years at least. Therefore, optimally preserved tests can be considered as members of the time-averaged biocoenosis (Yordanova & Hohenegger, 2007). According to Beavington-Penney (2004), *Palaeonummulites venosus* - the only living *Nummulites* s.l., failed to

demonstrate test damage caused through transport, which is often interpreted for fossil forms, despite simulating transport of large distance in coarse sand.

Only A forms were used, but the calculation here proposed may be used for both the generations and for all the nummulitids-like shapes.

Every specimen was measured on photographs taken either on thin sections or on complete tests. Photos of the equatorial section, the axial section and the external surface ornamentation were also measured. The vector image analysis program CanvasX was used. Basic calculations and statistics were performed in Microsoft EXCEL, while the program package SPSS for Windows, Release 16.0.1 was used for complex statistical analyses. All measurements were taken on large *Nummulites globulus* specimens, but it would have been possible to calculate the reaction to the hydrodynamic behaviour for every growth step (see Yordanova & Hohenegger, 2007). Every discussed parameter is reported in Tab. 1, the equations have numbers for an easier citation, and one (or two) letters for a quick link to Tab. 1.

PARAMETER CALCULATION

Size, shape and density

The parameters test length (L), width (I), height (S), and the areas of the equatorial and axial section were measured. Test length L (Tab. 1, column B) could directly be obtained on oriented thin sections or by image analysis on entire specimens immersed in water; the test width I (Tab. 1, column D) was measured perpendicularly to L crossing in the centre of the protoconch, while the test height S (Tab. 1, column F) was measured in axial section (Fig. 1).

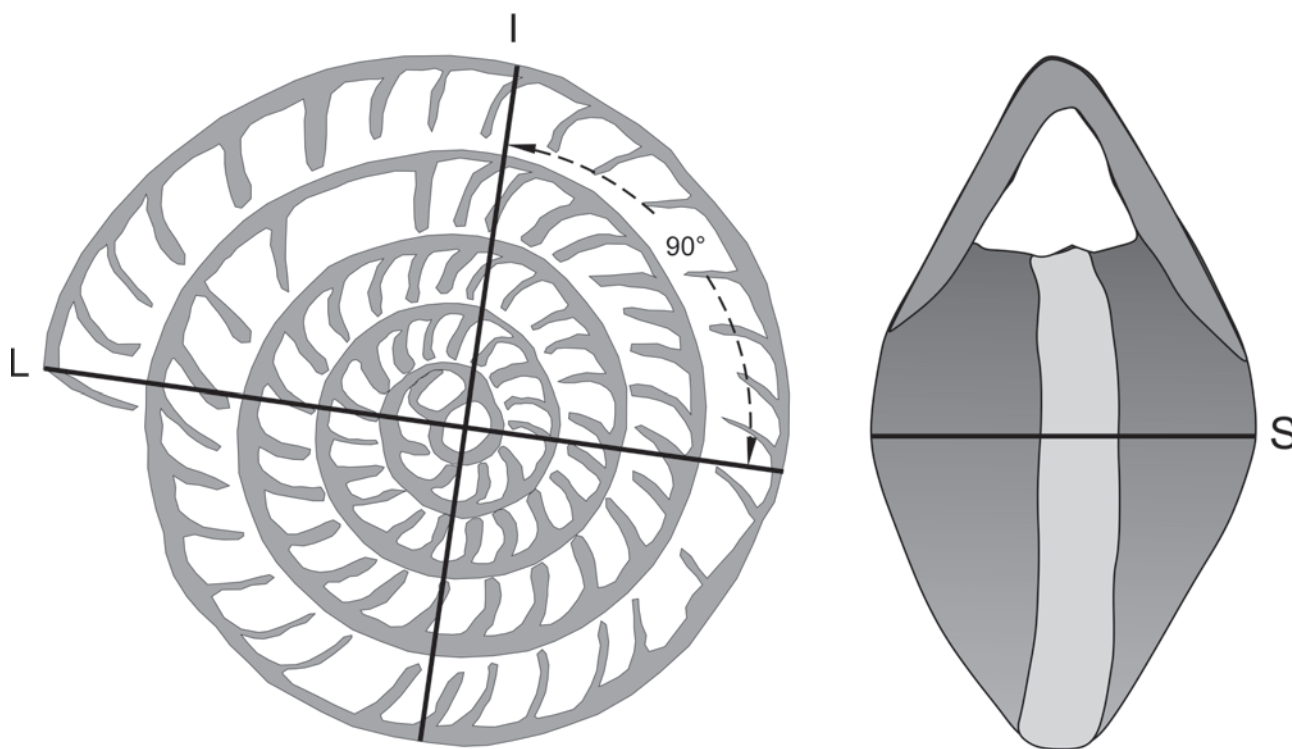


Fig. 1 - Sketches of equatorial section and axial view of a *Nummulites globulus*. L represents the highest length of the test, I must be perpendicular to L and both L and I must passing trough the protoconch. S represents the highest thickness.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
SPECIMEN	L		I		S		equat. area	axial area		V	TND	Dd	Dn	Wd	β	Uc*	P _i	P _i	P _a	Hr	Ws	We	Re	Cd	S. height	A	v
unit	μm	cm	μm	cm	μm	cm	μm^2	μm^2	cm ³	μm^3	cm		cm			cm/sec					cm/sec	cm/sec			cm	cm ²	cm/sec
4358	2112	0,21	1993	0,20	949	0,09	3155173	1143766	0,0017	1708342031	0,148	29,88	0,159	7,38	0,046	2,47	0,42	0,39	0,19	0,95	14,17	12,53	176	0,73	0,12	0,04	9,72
4362	2095	0,21	2062	0,21	880	0,09	3308383	1257483	0,0020	1985463997	0,156	29,40	0,156	7,29	0,046	2,46	0,42	0,41	0,17	0,94	14,00	12,07	179	0,79	0,11	0,04	10,21
4372	2225	0,22	2000	0,20	989	0,10	3322040	1374755	0,0021	2052768251	0,158	30,86	0,164	7,56	0,046	2,48	0,43	0,38	0,19	0,95	14,52	12,86	192	0,74	0,12	0,04	10,05
3514	2273	0,23	2142	0,21	969	0,10	3295659	1624262	0,0024	2354815126	0,165	31,59	0,168	7,69	0,046	2,49	0,42	0,40	0,18	0,95	14,77	12,85	201	0,75	0,12	0,04	10,50
4364	2401	0,24	2149	0,21	856	0,09	4069638	1412802	0,0024	2394421211	0,166	30,90	0,164	7,57	0,046	2,48	0,44	0,40	0,16	0,93	14,53	12,00	189	0,78	0,13	0,05	9,89
4336	2277	0,23	2155	0,22	952	0,10	3785594	1447322	0,0024	2406218864	0,166	31,49	0,167	7,67	0,046	2,49	0,42	0,40	0,18	0,94	14,73	12,74	201	0,76	0,12	0,04	10,54
3484	2345	0,23	2309	0,23	965	0,10	4043152	1400643	0,0024	2415387369	0,166	32,68	0,174	7,88	0,046	2,50	0,42	0,41	0,17	0,94	15,14	12,96	205	0,72	0,13	0,04	10,53
3506	2422	0,24	2198	0,22	940	0,09	4097253	1454530	0,0025	2460213317	0,167	32,22	0,171	7,80	0,046	2,49	0,44	0,40	0,17	0,94	14,98	12,71	202	0,74	0,13	0,05	10,17
3486	2464	0,25	2250	0,23	897	0,09	4282990	1483937	0,0026	2579566645	0,170	32,15	0,171	7,79	0,046	2,49	0,44	0,40	0,16	0,93	14,96	12,42	201	0,75	0,13	0,05	10,17
3512	2405	0,24	2218	0,22	1038	0,10	3874118	1655731	0,0027	2667296832	0,172	33,32	0,177	7,99	0,047	2,50	0,42	0,39	0,18	0,95	15,35	13,44	220	0,72	0,13	0,05	10,74
3467	2310	0,23	2117	0,21	1088	0,11	3685435	1697843	0,0027	2708283913	0,173	32,88	0,175	7,92	0,047	2,50	0,42	0,38	0,20	0,96	15,20	13,66	224	0,74	0,13	0,04	11,09
4360	2110	0,21	2075	0,21	1104	0,11	3475489	1681619	0,0028	2769901819	0,174	31,85	0,169	7,74	0,046	2,49	0,40	0,39	0,21	0,97	14,85	13,62	225	0,78	0,12	0,04	11,89
3518	2220	0,22	2104	0,21	1190	0,12	3448479	1870776	0,0029	2906349650	0,177	33,37	0,177	8,00	0,047	2,50	0,40	0,38	0,22	0,97	15,36	14,23	239	0,74	0,13	0,04	11,86
3494	2587	0,26	2378	0,24	1029	0,10	4751735	1841919	0,0034	3383343277	0,186	34,84	0,185	8,25	0,047	2,52	0,43	0,40	0,17	0,94	15,84	13,54	239	0,73	0,14	0,05	11,20
3474	2405	0,24	2234	0,22	1162	0,12	4141930	1964345	0,0034	3383361433	0,186	34,68	0,184	8,22	0,047	2,52	0,41	0,39	0,20	0,96	15,79	14,27	252	0,74	0,13	0,05	11,91
3496	2529	0,25	2450	0,24	1067	0,11	4927773	1774021	0,0035	3456452407	0,188	35,35	0,188	8,34	0,047	2,52	0,42	0,41	0,18	0,94	16,01	13,84	246	0,72	0,14	0,05	11,63
3400	2245	0,22	2028	0,20	1430	0,14	3300124	2414044	0,0035	3549069524	0,189	35,17	0,187	8,31	0,047	2,52	0,39	0,36	0,25	0,98	15,95	15,35	276	0,74	0,13	0,04	12,86
3502	2475	0,25	2456	0,25	1190	0,12	4646483	2113011	0,0040	3966368700	0,196	36,43	0,193	8,51	0,047	2,53	0,40	0,40	0,19	0,96	16,35	14,65	273	0,73	0,14	0,05	12,63
3394	2484	0,25	2346	0,23	1267	0,13	4643243	2323379	0,0043	4342756315	0,202	36,67	0,195	8,55	0,047	2,54	0,41	0,38	0,21	0,96	16,43	15,03	289	0,74	0,14	0,05	12,99

Tab. 1 - Geometric measurements and hydrodynamic parameters calculated on optimally preserved specimens of *Nummulites globulus* Leymerie 1846.

Because of further analyses, L , I , and S were measured in micrometer, but transformed to cm (Tab.1, columns C, E, and G). The measurement of L was taken as the largest test diameter, thus independent from the position of the second chamber (deuteroconch), which is sometimes used by morphologists for the determination of the diameter.

Calculating the contour area of fossilized organisms is not easy. There are many computer programs for calculating the area of an object using photographs (image analyses). These methods are fast and precise; they are perfect when dealing with living organism or optimally preserved specimens, where empty chambers and pores are still undistorted by any diagenetic process. Calculating the area of fossil forms could result in less precise values because of early diagenetic processes (Jorry et al. 2006). Even if fossils are optimally preserved, they could be slightly distorted or be damaged by preparation, and automated computer programs could over- or underestimate the required measurements. Because of this, the areas were calculated by reconstructing by hand the original shape's profile with the image analysis computer program. Area values in μm^2 can be found in columns H and I in Tab. 1.

Using equatorial and axial areas the test volume was calculated according to Yordanova & Hohenegger (2007), using the following formula

$$\text{Volume} = \frac{\text{area}_{\text{horizontal}} \cdot \text{area}_{\text{upright}}}{\text{maximum diameter}} \quad (1) - (\text{Tab. 1, column K})$$

For the calculation of test densities in fossil forms, several authors (Jorry et al., 2006; Yordanova & Hohenegger, 2007) pointed out good solutions and the values obtained show that the apparent density of *Nummulites* ranges from 1.7 to 1.9 g/cm^3 when the porous network is filled with seawater. Therefore, calculations were made on 'full-water' conditions (*sensu* Jorry et al., 2006) using an intermediate value of 1.8 g/cm^3 . This approximation is confirmed by the rather stable densities in *Palaeonummulites venosus* during growth (Yordanova & Hohenegger, 2007: Fig. 4). Data of recent nummulitids are thus comparable with this density value. Of course, for every organism and for every specimen it is possible to vary the value of this parameter in the formula to get a better approximation to the real hydrodynamic behaviour of every specimen.

Dimensionless analysis

Because of the non-linearity of the volume parameter depending on age (e.g., growth), it cannot be taken as a linear variable for calculating the interdependency of shape and hydrodynamic parameters (Yordanova & Hohenegger, 2007). Therefore, all volume values were transformed into a linear variable depending on age represented as the diameter of a sphere:

$$TND = 2 \left(\frac{3V}{4\pi} \right)^{1/3} \quad (2) - (\text{Tab. 1, column L})$$

where TND is the True Nominal Diameter proposed by Wadell (1932).

Such parameters, which do not take into account the original shape of an object, are called shape-independent; this peculiarity allows linear comparison within populations and to compare different populations without taking into account shapes differences; TND is also useful for growth analysis based on volumes as the representative parameter for age.

Thus it is always better to calculate the TND in cm using the correspondent volume calculated in cm^3 (Tab. 1, column J).

Jorry et al. (2006), for further dimensionless analyses, propose to use the parameter (D_d) to express the size of the equivalent sphere using the equation

$$D_d = \sqrt[3]{L \cdot I \cdot S} \cdot \sqrt[3]{\rho_f g \frac{(\rho_s - \rho_f)}{\mu^2}} \quad (3) - (\text{Tab. 1, column M})$$

where ρ_f is the density of the fluid, g is the gravitational acceleration, ρ_s is the density of the fossil and μ is the dynamic viscosity of the fluid. Using (3), this diameter is higher than the one obtained by equation (2), because (3) is multiplied by densities. Nevertheless, equation (3) becomes important to calculate shear and settling velocities, and further calculations will reduce this difference.

A similar value to (2) can be obtained using the formula proposed by Le Roux (1997)

$$D_n = \sqrt[3]{L \cdot I \cdot S} \quad (4) - (\text{Tab. 1, column N})$$

For the analysis reported here, which regards lentil-shaped tests as can be found in nummulitids, the use of (4) is preferred, while for tests with irregular shape (i.e. calcarinids, peneroplids) the use of the TND must be preferred. The best solution for evaluating the volume in case of irregular tests is measuring in liquid mercury (Hg) because it is a non-wetting fluid (Jorry et al., 2006).

Shear and settling velocities

It is now possible to calculate the settling velocities acting as multipliers for different scales. Le Roux (1997) and Jorry et al. (2006) propose the "dimensionless sphere settling velocity" (W_d):

$$\begin{aligned} &\text{for } D_d < 134.9 \\ &W_d = -0.375 + 0.29D_d - 0.002D_d^2 + 4.731 \times 10^{-6}D_d^3 \end{aligned} \quad (5) - (\text{Tab. 1, column O})$$

This formula is a series expansion: a mathematical representation of a function as an infinite sum of terms calculated from the values of its derivatives at a single point. Because of the very low third coefficient, calculations of higher terms would give no improvement. Because W_d is calculated using D_d , which is mathematically size and shape independent, its results are also size and shape independent.

For $D_d > 134.9$ other solutions are proposed, but for the typical size range of symbiont-bearing benthic foraminifera, the value of 134.9 can only be found in giant B-generations of nummulitids when measured in mm.

According to Jorry et al. (2006), the dimensionless critical shear stress (β) is calculated in the following way

$$\beta = 0.029 + 0.003W_d - 9.935 \times 10^{-5}W_d^2 \quad (6) - (\text{Tab. 1, column P})$$

for $W_d > 2.5$

Here, the second-degree series is precise enough to describe the nummulitid's stress behaviour with a scale-independent settling velocity value higher than 2.5.

As published by Jorry et al. (2006), the critical shear velocity (U_c) becomes

$$U_c = 1.959 + 0.253 \sqrt{\beta g \left(\frac{\sqrt{L \cdot I \cdot S}}{1.32} \right) \frac{(\rho_s - \rho_f)}{\rho_f}} \quad (7) - (\text{Tab. 1, column Q})$$

Comparing the results obtained through these set of formulas with published data (Yordanova & Hohenegger, 2007; Jorry et al., 2006; Davaud & Septfontaine, 1995) shows slight incongruence, probably due to peculiar environmental factors and laboratory settings.

Settling velocity is the most important parameter characterizing the behaviour of grains in fluids. Due to gravity the settling properties of the foraminiferal test act against the energy input induced by water movement.

An input higher than its settling velocity is required to keep the test in suspension leading to transport. High settling velocities push the tests to the ground because of gravity, while low settling velocities, typical for flat nummulitids like assilinitids and operculinids, can keep the test in suspension and expose it to transport.

A set of formulas was used to calculate more precise settling velocities of tests with specific morphologies deviating from a spherical or ellipsoid grain.

The settling velocity of the equivalent sphere (W_s) proposed by Le Roux (1996) was calculated using

$$W_s = \frac{W_d}{\sqrt[3]{\frac{\rho_f^2}{\mu g (\rho_s - \rho_f)}}} \quad (8) - (\text{Tab. 1, column V})$$

The next step to obtain the real settling velocity of a particle must consider the entropy of the test. In fact, the difference between the settling velocity of a sphere and a non-spherical particle with the same volume is directly related to the deviation from sphericity, where grain roundness plays a negligible role (Briguglio, 2009).

The shape entropy is an important value in hydrodynamics. Concerning nummulitids, the entropy is the most important parameter that produces differences in settling and, consequently, in transport. The best formula to calculate shape entropy is proposed by Hofmann (1994). It is based on the geometry of an ellipsoid and can be calculated with

$$H_r = -[(p_l \times \ln p_l) + (p_i \times \ln p_i) + (p_s \times \ln p_s)] / 1.0986 \quad (9) - (\text{Tab. 1, column U})$$

where p_p , p_i and p_s are the proportions of the major, intermediate and minor axes of the ellipsoid

$$\begin{aligned} p_l &= I / (L + I + S) \\ p_i &= L / (L + I + S) \\ p_s &= S / (L + I + S) \end{aligned} \quad (10) - (\text{Tab. 1, columns R, S, and T}).$$

Knowing the entropy of a non-spherical grain, its settling velocity (W_e) can be calculated using the equation of Le Roux (1996)

$$W_e = W_s [(H_r - 0.5833) / 0.4167] \quad (11) - (\text{Tab. 1, column W})$$

According to Le Roux (2004), equation (11) yields a mean accuracy of 95.7% of W_e with experimental data

Other hydrodynamic parameters

Allen (1984), studying the settling velocity of bivalve shells, discovered that a valve allowed to fall freely in a large volume of plain stagnant water at first accelerates, but finally reaches a steady terminal fall velocity given by the equation:

$$v^2 = \frac{2gV(\rho_s - \rho_f)}{C_D \rho_f A} \quad (12) - (\text{Tab. 1, column AB})$$

where C_D is the drag coefficient, A is the projected area of the shell assumed during sinking, v is the vertical component of the terminal fall velocity and V is the volume. Particles, shells and also fossil nummulitids orient their maximum projection area in the direction of settling (Komar & Reimers, 1978) and this condition reduces sinking velocity in the same way as low test densities (Yordanova & Hohenegger, 2007).

Defining the parameters A and C_D of (12) is difficult. Calculation of the area directed to the flow is complicated in nummulitids. An alternative solution, proposed by Briguglio (2008) shows good results by comparing the nummulitids test to a solid object composed by two equal cones bound by the basal area. This basal area would be the parameter A , calculated as follows

$$A = (\pi r^2 + \pi r s) / 2 \quad (13) - (\text{Tab. 1, column AA})$$

where

$$s = \sqrt{r^2 + h^2} \quad (14) - (\text{Tab. 1, column Z})$$

is the slant height.

The Reynolds number and the drag coefficient C_D , according to Le Roux (1997), are given by

$$\text{Re} = \frac{\rho_f D_n W_e}{\mu_f} \quad (15) - (\text{Tab. 1, column X})$$

and

$$C_D = \frac{4D_n g (\rho_s - \rho_f)}{3\rho_f W_e^2} \quad (16) - (\text{Tab. 1, column Y})$$

where D_n and W_e are already calculated in (2) and (11).

The relation between C_d and Re for *N. globulus* matches with the equation that relates C_d and Re of a sphere as proposed by Abraham (1970)

$$C_D = C_0 \left(1 + \frac{\delta_0}{\sqrt{\text{Re}}} \right)^2 \quad (17)$$

where

$$\delta_0 \cong 9.06 \text{ and } C_0 \delta_0^2 = 24$$

RESULTS

The resulting hydrodynamic parameters obtained by different mathematical analysis were compared with experimental data obtained on recent foraminifera and published by Yordanova & Hohenegger (2007). The comparison between *Nummulites venosus* and *N. globulus* demonstrates good results: Reynolds number values and the relations between test length and test width and height show the same trend (Briguglio & Hohenegger, 2008). This clearly demonstrates the correctness of the calculation methods and they can now be used for the interpretation of the hydrodynamic behaviour of all nummulitids independent of their size, because the calculation is based on scale- and shape-independent parameters.

They could be applied in shallow water as well as in deep-water environment.

The shape-independent diameters can be used for comparison between forms in different environments as well as within assemblages. In an energetic scenario, the distribution of forms creates assemblages with restricted settling velocities and nominal diameter values; i.e. along a slope, a variation of settling velocities vs. nominal diameters ratio can be recognized from shallower environments to deeper ones.

The entropy value is fundamental for the calculation of the settling velocity, showing how less important size is in comparison with shape or density. At the same time, shape is the most powerful variable to understand and evaluate the distribution of different tests along a slope, as demonstrated by outcrop studies (Jorry et al., 2003; Racey, 2001).

The particle's Reynolds number is used to indicate whether the boundary layer around a particle is turbulent or laminar, and the drag exerted will depend on this. Understanding and quantifying the turbulence produced by a test (or even a shell) at the sea floor would probably give an advance for understanding the hydrodynamic of the huge amount of tests to evaluate their accumulation, e.g. the so called "nummulite banks", which are very abundant in the Eocene rocks in many locations of Europe and northern Africa.

The correlation found between the drag coefficient C_d and the Reynolds number Re , at the end of all this mathematic calculation, allows the use of all formula and data obtained solely by geometrical analysis without any laboratory experiment. This does not mean that the value obtained is absolutely correct, but the whole process is rigorous and the errors are only statistical and not fundamental.

More information will be obtained by further investigations, when other parameters could also be investigated. However, theoretical models and empirical correlations are affected by limits due to the large amount of environmental factors influencing hydrodynamics factors; furthermore, additional data especially from the fossil record are required to improve their accuracy and increase their ranges of applicability.

CONCLUSIONS

The correlation between fossil and recent forms demonstrates the perfect coincidence of hydrodynamic parameters up to the Reynolds numbers. In this way, the distribution of different nummulitids that lived on the slope or ramp could be explained by their hydrodynamic behaviour. The ecological cause-effect scenario (abundance, biodiversity, interaction among species) is rarely full preserved in the fossil record, and only in some exceptional preservation cases can be completely reconstructed; the *post mortem* cause-effect scenario (e.g., energy input, distribution by transport, destruction) may be recognized and calculated and it may help for a better environmental determination.

These calculations show in which way hydrodynamic parameters may be fundamental to evaluate the distribution of larger foraminifera in recent and fossil environments. On the base of our analysis and results, the physical parameters seem to be important same as the biological and ecological factors which works as inputs in the environment, thus we consider that a calculation like the one here presented should be performed in every paleoenvironmental reconstruction, especially in shallow water environments where the hydrodynamics is a prominent tool and may be used to evaluate physical phenomena and to improve the knowledge of geometrical forms distribution along a ramp during *in vita* and *post mortem* time spans.

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APPENDIX 1

Nomenclature used in text:

- $L = D_l$ = large diameter (length)
 $I = D_i$ = intermediate diameter (width)
 $S = D_s$ = small diameter (height or thickness)
 TND = True nominal diameter
 V = volume
 D_d = dimensionless size of the equivalent sphere
 D_n = true nominal diameter according to Le Roux (1997)
 W_d = dimensionless sphere settling velocity
 β = critical shear stress
 U_c = critical shear velocity
 H_r = shape entropy
 $p_l p_i p_s$ = proportion between the axis calculated with (9)
 W_e = settling velocity of a non spherical grain
 W_s = settling velocity of the equivalent sphere
 C_d = drag coefficient
 A = area of the shell/test contrasting the water during sinking
 v = vertical component of the terminal fall velocity.
 Re = Reynolds number
 ρ_f = density of the fluid (seawater) = 1.025 g cm^{-3}
 ρ_p = density of the fossil = 1.8 g cm^{-3}
 μ^s = dynamic viscosity of the fluid (seawater) = $0.0108 \text{ g (cm s)}^{-1}$
 g = gravity constant = $981.0327 \text{ cm sec}^{-2}$