Published in final edited form as:

. 2012 April 1; 42(2): 134–142. doi:10.2113/gsjfr.42.2.134.

AXIALLY ORIENTED SECTIONS OF NUMMULITIDS: A TOOL TO INTERPRET LARGER BENTHIC FORAMINIFERAL DEPOSITS

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Abstract

The “critical shear velocity” and “settling velocity” of foraminiferal shells are important parameters for determining hydrodynamic conditions during deposition of *Nummulites* banks. These can be estimated by determining the size, shape, and density of nummulitid shells examined in axial sections cut perpendicular to the bedding plane. Shell size and shape can be determined directly from the shell diameter and thickness, but density must be calculated indirectly from the thin section. Calculations using the half-tori method approximate shell densities by equalizing the chamber volume of each half whorl, based on the half whorl’s lumen area and its center of gravity. Results from this method yield the same lumen volumes produced empirically by micro-computed tomography. The derived hydrodynamic parameters help estimate the minimum flow velocities needed to entrain nummulitid tests and provide a potential tool to account for the nature of their accumulations.

INTRODUCTION

Accumulations of *Nummulites* and *Assilina* are common in late Paleocene to early Oligocene carbonate deposits, and differing hypotheses have attempted to explain the causes of their extraordinarily diverse geometry, texture, and composition (Jorjy and others, 2006, and reference therein). Some authors consider these larger foraminiferal accumulations as either shelf-edge detritus (e.g., Arni, 1965) or ramp deposits (e.g., Comte and Lehman, 1974). Others regard such accumulations as reworking in high-energy environments, in which shells were transported by wave- or tide-induced currents or concentrated by storm events (e.g., Racey, 2001). Aigner (1985) attributed some of these accumulations to repeated winnowing, whereas Mateu-Vicens and others (2011) recently explained them as concentrated by internal waves.

These hypotheses could be tested if we knew the hydrodynamic conditions at the time of deposition. Because nummulitids probably hosted photosymbionts, their depth ranges likely coincided with at least one of several hydrodynamic processes such as surface waves, internal waves, and currents. Upon death each shell became a sediment grain, which enables calculating its transportability (sensu Briguglio and Hohenegger, 2011). Making those calculations on a range of shells in a nummulite deposit can yield frequency distributions of the hydrodynamic parameters “critical shear velocity,” indicating the necessary force to

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entrain shells, and “settling velocity,” a measure for suspension and transportability. The lower limit of these frequency distributions and their dispersion parameters (e.g., standard deviation) points to the intensity of hydrodynamic forces that acted during shell deposition.

Calculating the above hydrodynamic parameters requires determination of shell size, shape, and density (Jorjy and others, 2006; Yordanova and Hohenegger, 2007; Briguglio and Hohenegger, 2009). These measurements are easy to perform on Recent foraminifera (Yordanova and Hohenegger, 2007) but more difficult on indurated nummulitids, in which sedimentary or diagenetic fillings have closed the test lumen. Although size and shape can be inferred directly from the shell diameter and thickness measured in preferred axial sections, shell densities cannot be quantified because it is impossible to measure the shell lumen, which consists of chamber volumes, the canal system, and pores.

This paper presents a method for estimating lumen volumes based on axial sections of Nummulitidae, thus making shell density estimates feasible. From these data it is possible to recreate the hydrodynamic conditions that controlled the deposition of nummulite-rich sediments in the Paleogene.

MATERIAL AND METHODS

Two optimally preserved fossil tests with minimal chamber fillings and two Recent foraminifera were used to calculate density estimates. The Recent ones, both from Okinawa, Japan, include *Palaeonummulites venosus* (Fichtel and Moll), collected from a 50-m depth west of Sesoko Jima, and *Operculina ammonoides* (Gronovius), collected from an 18-m depth in the lagoon west of Motobu town (Hohenegger, 1994). A late Eocene *Nummulites fabianii* (Prever) from Cluj-Napoca, Romania, and an early Oligocene *N. fichteli* (Michelotti) from Biarritz, rocher de la Vierge, SW France, represent the fossil forms.

Each specimen was scanned with a micro-computer tomograph (Micro-CT) at the Department of Theoretical Biology, University of Vienna. The key advantages of X-ray CT are its ability to reconstruct quickly and nondestructively the three-dimensional interior of opaque solid objects, if the density contrast is high enough to let the X-ray differentiate the internal features (Neues and Epple, 2008). It can also quantify almost any two- and three-dimensional measurement, including the volumes and surfaces of the lumina of all four scanned specimens. A dedicated three-dimensional visualization program extracted the virtual equatorial and axial sections. For each of the latter, the overall shell area was measured, as well as the area of each chamber visible in the axial section (Fig. 1). For each chamber, the distance between its center of mass (i.e., centroid or center of gravity) and the center of the proloculus was also determined by image analysis. The EXCEL program TORICALC (Appendix 1), developed by the senior author, was used for the calculations.

CALCULATIONS

Measurements

Based on axial sections, two approaches are presented here to estimate nummulitid lumen volume, which is the sum of a) chamber volumes, b) the lateral reticulate pattern, c) the

canal system, and d) pores. Volumes a and b are termed macropores, and c and d micropores (Jorjy and others, 2006). In living foraminifera the lumen is filled with cytoplasm that is replaced by sea water in dead shells.

Initially the area A_{shell} of the axial section must be obtained by image analysis, where the radii R_1 , R_2 , and R_3 , and the thickness H of the axial section are measured as displayed in Figure 1.

The area $A_{ellipse}$ of an ellipse using the above linear measurements results from

$$A_{ellipse} = \pi (DH/4), \quad (1)$$

where

$$D = \sqrt{R_1 R_3 + R_2^2} \quad (2)$$

in the case of an unknown position of the axial section (e.g., not cutting the final chamber).

Based on areas A_{shell} and $A_{ellipse}$, the volume of a spheroid approximating the empirical volume of the shell ($V_{spheroid} \approx V_{shell}$) can be obtained by

$$V_{spheroid} = \left[4\pi (D/2)^2 (H/2) / 3 \right] \left(\sqrt{A_{shell}/A_{ellipse}} \right)^3. \quad (3)$$

For estimating the volume of the shell lumen, all areas a_i belonging to a half whorl and distances d_i of their centers of gravity to the proloculus center (index 0) have to be measured in increasing order (Fig. 1), formally described as

$$a_0, a_1, a_2, \dots, a_i, \dots, a_n \quad \text{and} \quad d_1, d_2, \dots, d_i, \dots, d_n$$

$n = \text{number of half whorls.}$

The volume of the shell lumen has been obtained here in two ways: “the half-tori method with constant radius r ” and the “half-tori method with increasing radius r ,” where the volume of the proloculus is approximated in both methods by

$$v_0 = 4\pi \left(\sqrt{a_0/\pi} \right)^3 / 3. \quad (4)$$

Half-Tori Method With Constant Radius

Chamber volumes and other lumina will be regarded as half tori (i.e., half donuts), where the measured area a_i of a half whorl in axial section will be replaced by a circle with radius

$$r_i = \sqrt{a_i/\pi} \quad (5)$$

possessing an identical area to the cross section area (Figs. 1, 2A). The center of the circle must be positioned at the center of gravity of the half whorl (Fig. 1). Now, a half torus can approximate the lumen volume of the half whorl i by

$$v_i = \pi d_i a_i. \quad (6)$$

When the axial section cuts the final chamber, the volume of the torus becomes

$$v_n = (\pi d_n a_n) / 2.$$

Half-Tori Method With Increasing Radius

In this method, both circles limiting a half torus differ in size, thus representing the continuous increase in lumen volumes (Figs. 1, 2B). The beginning and end of the half torus is determined by circles with the radii

$$r_{1i} = (\sqrt{a_i a_{i-1}} / \pi)^{1/2} \quad (7)$$

$$r_{2i} = (\sqrt{a_i a_{i+1}} / \pi)^{1/2}. \quad (8)$$

For the first half whorl the radius of the initial circle can be approximated by

$$r_{11} = \left(\sqrt{a_i^3 / a_{i+1}} / \pi \right)^{1/2} \quad (9)$$

while for the last half whorl the radius of the final circle is approximated by

$$r_{2n} = \left(\sqrt{a_n^3 / a_{n-1}} / \pi \right)^{1/2}. \quad (10)$$

The radius of a half torus d_i^* is given by

$$d_i^* = \left(\sqrt{d_i d_{i-1}} + \sqrt{d_i d_{i+1}} \right) / 2 \quad (11)$$

with the exception of

$$d_1^* = d_1 \quad \text{and} \quad d_n^* = \left(\sqrt{d_n d_{n-1}} + \sqrt{d_n^3 / d_{n-1}} \right) / 2. \quad (12)$$

Now the volume of a half torus with increasing radius r of half whorl i can be calculated by

$$v_i = \left(d_i \pi^2 / 3 \right) \left(r_{1i}^2 + r_{1i} r_{2i} + r_{2i}^2 \right). \quad (13)$$

Lumen Volume and Shell Density

With both methods, the volume of the shell lumen V_{lumen}^* is given by

$$V_{lumen}^* = \sum_{i=1}^{i=n} v_i \quad (14)$$

and can be related to the shell volume $V_{spheroid}$ by the percentage

$$100 \cdot V_{lumen}^* / V_{spheroid} \quad (15)$$

To estimate the true density of a foraminiferal shell, the micropore lumen has to be added, which is difficult to measure in axial sections. Therefore, the micropore space

$$V_{micropores} = (V_{spheroid} - V_{lumen}^*) \cdot p(micropore) \quad (16)$$

must be assumed by observations based on the proportion p of pore space in the shell wall using an SEM or NannoMicro-CT. The pore space has to be subtracted from the shell volume, yielding the true volume of the shell lumen

$$V_{lumen} = V_{lumen}^* + V_{micropores} \quad (17)$$

With volumes $V_{spheroid}$, $V_{wall} = V_{spheroid} - V_{lumen}$ and V_{lumen} , estimations of the shell density ρ are possible by

$$\rho_{shell} = (V_{wall}\rho_{material} + V_{lumen}\rho_{filling}) / V_{spheroid} \quad (18)$$

where the shell wall is calcite and the lumen filling can be seawater, cytoplasm, or air.

VOLUME ESTIMATION

Results of these calculations to estimate lumen volume were applied to two Recent and two fossil larger foraminiferal specimens selected for this study. Basic axial measurements are shown in Table 1. The empirical lumen volume of the Recent specimens *Palaeonummulites venosus* and *Operculina ammonoides* (Fig. 3) obtained by Micro-CT was slightly lower than using the axial section methods (Table 2, Fig. 4). For *P. venosus*, the half-tori method of constant radii yielded better results than the one using increasing radii. In contrast, the increasing half-tori radii method estimated the lumen volume better in *O. ammonoides* (Table 2, Fig. 4).

The slight but significant overestimation in both methods is caused by disregarding the volume of the septa, which must be subtracted from the lumen volume. Septal volumes can be estimated only in equatorial sections of the same specimen from which the axial section is taken, an impossibility in sedimentary rocks. Despite this handicap, the estimate of the lumen volume in proportion to the total shell volume is very good in the Recent specimens (Table 2), especially comparing the empirical proportion in *O. ammonoides* (37.5%) with the theoretical proportion obtained by the half-tori method using increasing radii (38.6%).

The lentil-shaped shells of both fossil specimens *Nummulites fichteli* and *N. fabianii* (Fig. 5) led to precise estimates of shell volumes based on spheroids (Table 2). Lumen volume estimates by both half-tori methods again approximate almost exactly the empirical values (Table 2). Theoretical volumes in *N. fabianii* were 16.2% and 16.7% versus 16.5% empirical, and in *N. fichteli* 19.2% and 18.9% versus 19.6%.

DENSITY ESTIMATION

Estimating the exact density of a foraminiferal shell requires incorporating the lumen volume of the micropores (pores and canals) (equation 18). Measurements on Recent nummulitid shell walls yielded pore volume proportions between 0.08–0.22 (Briguglio and others, 2011). This value is lower than the measured pore volume for fossil *Nummulites* (between 0.25–0.36; Jorjy and others, 2006). Moreover, the proportion of the canal system has to be estimated because measurement of that system in axial sections is impossible. In this case, a micropore proportion between 0.20–0.40 may be assumed.

Densities of air-filled *Operculina ammonoides* and *Palaeonummulites venosus* shells were obtained by relating the weight measured with a micro balance to the shell volume obtained by Micro-CT (Table 3). These densities were compared with densities using the empirical relations between wall and air-filled lumen volumes, both obtained by Micro-CT, based on equation (18). Different proportions of micropores were used to approximate the densities obtained by weighing. The optimum proportion of micropores is 0.335 for *P. venosus* and 0.20 for *O. ammonoides* (Table 3).

Comparing the empirical densities based on Micro-CT volume, estimates with the two half-tori methods reveals a slight underestimation in both of the latter, although the approach based on increasing radii leads to better approximations (Table 3). The verified quality of these theoretical methods enables calculating the density of living shells filled with cytoplasm or empty ones with seawater (Table 3), both being important considerations in marine transport. Densities of both Recent species differed when the shells were filled with seawater, with values of 1.83 for *P. venosus* and 1.87 for *O. ammonoides*; the half-tori estimates yielded slightly lower densities of 1.79 and 1.86, respectively. Density estimates using measured volumes and the half-tori approximation coincided better in both fossil specimens (Table 3). Under the assumption of a 30% pore volume filled with sea water, the empirical and theoretical density of *N. fabianii* at $\rho = 2.01$ is somewhat higher than that of *N. fichteli* at $\rho = 1.98$.

HYDRODYNAMICS ESTIMATION

With mean shell diameter D and shell thickness H , the most important hydrodynamic parameters of critical shear velocity and settling velocity can be calculated for a single specimen. Flow velocities above the critical shear velocity, depending on the substrate (Yordanova and Hohenegger, 2007), dislodge the shell from the sediment surface, while velocities above the settling velocity keep the shell in suspension and transport (Yordanova and Hohenegger, 2007; Briguglio and Hohenegger, 2009). The calculation of these hydrodynamic parameters follows the equations given in Le Roux (1997), Jorjy and others (2006), and Briguglio and Hohenegger (2009), and the results are shown in Table 4.

Critical shear velocity is similar for the Recent specimens *Palaeonummulites venosus* at 2.3 cm/sec and *Operculina ammonoides* at 2.4 cm/sec, and identical for the fossil specimens *Nummulites fabianii* and *N. fichteli* at 2.5 cm/sec. The entrainment of a sediment grain depends on the roughness of the substrate, the type of water movement, and shell shape. Therefore, the velocity necessary for entrainment is much higher than the critical shear velocity (Yordanova and Hohenegger, 2007). Nevertheless, critical shear velocities can be used to compare entrainment differences between species and between ontogenetic stages of differing shapes within a species.

Settling velocity is important for interpreting transport. The Recent specimens *P. venosus* at 9.39 cm/sec and *O. ammonoides* at 8.09 cm/sec show lower settling velocities compared to the fossils *N. fabianii* at 12.79 cm/sec and *N. fichteli* at 11.65 cm/sec. These differences are caused by the size of the *Nummulites* specimens, which is double that of both Recent forms. Current velocities higher than settling velocities keep specimens in suspension, and transport distance depends on the intensity and decrease of current velocity and on slope inclination (Hohenegger and Yordanova, 2001). Furthermore, the influence of orbital velocities most important for entrainment and transport in suspension can be calculated based on settling velocity and critical shear stress velocity (Briguglio and Hohenegger, 2011).

SUMMARY

Larger fossil foraminifers can be used to estimate ancient hydrodynamic conditions through the manipulation of size, shape, and density data obtained from axially oriented thin and polished sections. While size and shape are directly related to the shell diameter and thickness, density measurements depend on estimated shell and lumen volumes. To obtain these volume estimates the foraminiferal shell is geometrically replaced by a spheroid of the same volume, configured from the diameter and thickness of the original shell.

The lumen volume of the macropores (chambers and lateral reticulate pattern), originally filled by cytoplasm and later replaced by seawater, can be estimated by two half-tori methods, one based on constant radii and the other on increasing radii. Both methods yield excellent estimates of chamber volumes as confirmed by Micro-CT analysis. The lumen volume of the micropores (pores and canals) are virtually impossible to derive from thin section but can be estimated by subtracting an average micropore volume (determined from experience with well-preserved shells) from the wall volume and adding it to the shell lumen volume.

Specimen shell density can be calculated by multiplying a) the wall volume with the density of calcite and b) the lumen volume with the density of air, seawater, or cytoplasm. The shell density would then be the sum of a) and b) divided by shell volume.

With the above information the important hydrodynamic parameters of critical shear velocity and settling velocity can be calculated for every axially oriented specimen. Combined with other sedimentary features, knowledge of these parameters could contribute enormously to interpreting the hydrodynamic conditions—still mostly unknown—responsible for nummulitid accumulations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENT

This is the first paper published within the project P 23459-B17 “Functional Shell Morphology of Larger Benthic Foraminifera” of the Austrian Science Fund. First we thank György Less, University of Miskolc, for supplying excellently preserved fossil *Nummulites* specimens. Thanks are due to Gerd Müller and Brian Metcher, University of Vienna, for providing access to the Micro-CT, as well as Cesare Papazzoni and Mona Seddighi, University of Modena, for posing the problem of density estimations of foraminiferal shells in thin sections. Finally, we thank Simon Beavington-Penney, BG Group Reading, and Guillem Mateu-Vicens, University de les Illes Balears, for useful suggestions in their reviews. Michael Stachowitsch, University of Vienna, revised the English text as a native English-speaking scientific copy editor, and editors Pamela Hallock and Paul Brenckle made the paper more concise and read more smoothly.

APPENDIX 1

Calculations of the half-tori method, using the TORICALC program, can be found on the Cushman Foundation website in the JFR Article Data Repository (<http://www.cushmanfoundation.org/jfr/index.html>) as item number JFR_DR2012004.

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Figure 1.

Axial section parameters measured in *Operculina ammonoides* (shown) and other species (see Table 1). Chamber lumen area (in gray) and center of gravity (x) for each half whorl must be obtained by image analysis. Circles represent identical area of each half-volution lumen and are positioned at its center of gravity (further explanation in the text).

Figure 2. Estimates of shell lumina by the half-tori method. **A** lateral view of half tori with constant radius; **B** lateral view of half tori with increasing radius.

Figure 3. Micro-CT graphs of *Palaeonummulites venosus* (upper row) and *Operculina ammonoides* (lower row). **a** micrograph showing all chambers; **b** equatorial section; **c** axial section cutting the final chamber; **d** areas of shell lumina in axial section.

Figure 4.
Comparison of shell lumina volumes based on Micro-CT measurements and half-tori radii estimates.

Figure 5. Micro-CT graphs of *Nummulites fabianii* (upper row) and *N. fichteli* (lower row). **a** micrograph showing all chambers; **b** equatorial section; **c** axial section cutting the final chamber; **d** areas of shell lumina in axial section.

Table 1

Measurements of axial sections in mm. See Figure 1 for terminology.

	<i>Palaeonummulites venosus</i>		<i>Operculina ammonoides</i>		<i>Nummulites fabianii</i>		<i>Nummulites fichteli</i>	
total area A	1.263		0.915		2.613		2.733	
radius R_1	1.013		1.071		1.831		1.900	
radius R_2	0.878		1.013		1.672		1.973	
radius R_3	0.721		0.550		1.526		1.571	
thickness H	1.031		0.791		1.083		1.042	
	area	distance	area	distance	area	distance	area	distance
proloculus	0.0063		0.0032		0.0762		0.0799	
half whorl								
1	0.0020	0.064	0.0032	0.045	0.0322	0.204	0.0190	0.197
2	0.0055	0.079	0.0030	0.104	0.0227	0.253	0.0130	0.285
3	0.0079	0.122	0.0130	0.134	0.0123	0.448	0.0080	0.387
4	0.0166	0.150	0.0175	0.200	0.0182	0.436	0.0120	0.540
5	0.0250	0.223	0.0357	0.267	0.0157	0.666	0.0120	0.627
6	0.0518	0.271	0.0498	0.318	0.0413	0.601	0.0230	0.555
7	0.0450	0.402	0.0967	0.563	0.0252	0.589	0.0360	0.545
8	0.0983	0.485	0.1275	0.658	0.0351	0.826	0.0440	0.759
9	0.1615	0.646			0.0672	0.903	0.0660	0.731
10					0.0884	0.622	0.0450	0.752
11					0.1363	0.950	0.0760	0.871
12							0.1130	0.856
13							0.0990	1.007

Table 2

Shell and lumen volumes estimated by the theoretical half-tori methods of constant and increasing radii compared to the empirical volumes measured by Micro-CT (units in mm³).

	<i>Palaeonummulites venosus</i>		<i>Operculina ammonoides</i>		<i>Nummulites fabianii</i>		<i>Nummulites fichteli</i>	
shell volume empirical	1.308		0.881		5.791		6.594	
shell volume theoretical	1.384		0.988		5.641		6.405	
	lumen volume		lumen volume		lumen volume		lumen volume	
Proloculus	0.00038		0.00014		0.01583		0.01699	
	half torus		half torus		half torus		half torus	
	constant	increasing	constant	increasing	constant	increasing	constant	increasing
half whorl								
1	0.0004	0.0004	0.0005	0.0004	0.0206	0.0200	0.0119	0.0114
2	0.0014	0.0013	0.0010	0.0013	0.0181	0.0192	0.0117	0.0116
3	0.0030	0.0033	0.0055	0.0046	0.0173	0.0194	0.0099	0.0126
4	0.0078	0.0078	0.0110	0.0123	0.0249	0.0245	0.0210	0.0182
5	0.0175	0.0187	0.0299	0.0272	0.0329	0.0387	0.0241	0.0266
6	0.0441	0.0380	0.0497	0.0619	0.0780	0.0556	0.0401	0.0403
7	0.0569	0.0693	0.1709	0.1448	0.0466	0.0629	0.0616	0.0640
8	0.1498	0.1489	0.1318	0.1289	0.0912	0.0951	0.1049	0.1017
9	0.1639	0.1599			0.1906	0.1578	0.1516	0.1265
10					0.1727	0.2216	0.1063	0.1376
11					0.2034	0.2141	0.2080	0.1969
12							0.3039	0.2791
13							0.1566	0.1699
	theoretical		theoretical		theoretical		theoretical	
lumen volume	0.4451	0.4480	0.4004	0.3817	0.9122	0.9447	1.2285	1.2133
percentage	32.2	32.4	40.5	38.6	16.2	16.7	19.2	18.9
	empirical		empirical		empirical		empirical	
lumen volume	0.3667		0.3306		0.9574		1.2922	
percentage	28.1		37.5		16.5		19.6	

Table 3

Comparison of shell, wall, and lumen volumes (chamber lumina + estimated microporosity) and shell density measured empirically by Micro-CT and theoretically by half-tori methods (units in mm³). Density estimates are for shells filled completely with air, seawater, or cytoplasm.

	<i>Palaeonummulites venosus</i>			<i>Operculina ammonoides</i>			<i>Nummulites fabianii</i>			<i>Nummulites fichteli</i>		
	empirical	theoretical	half torus	empirical	theoretical	half torus	empirical	theoretical	half torus	empirical	theoretical	half torus
shell volume	1.308	1.384	0.881	0.988	5.791	5.641	6.594	6.405				
	empirical	constant	increasing	empirical	constant	increasing	empirical	constant	increasing	empirical	constant	increasing
wall volume	0.6209	0.6198	0.6179	0.4403	0.4700	0.4849	3.3835	3.3100	3.2872	3.7113	3.6237	3.6343
lumen volume	0.6876	0.7644	0.7663	0.4407	0.5179	0.5029	2.4075	2.3307	2.3535	2.8827	2.7815	2.7709
proportion micropores	0.335			0.20			0.30			0.30		
density	1.85	1.81	1.81	1.89	1.85	1.88	2.03	2.03	2.03	1.99	2.00	2.00
cytoplasm												
seawater	1.83	1.79	1.79	1.87	1.83	1.86	2.01	2.02	2.01	1.98	1.98	1.98
air	1.30	1.23	1.23	1.36	1.30	1.34	1.59	1.60	1.58	1.53	1.54	1.54
empirical density (air)	1.30			1.36								

Table 4

Calculation of hydrodynamic parameters from axial measurements and estimates based on the half-tori method of increasing radii.

	<i>Palaeonummulites venosus</i>	<i>Operculina ammonoides</i>	<i>Nummulites fabianii</i>	<i>Nummulites fichteli</i>
diameter D in mm	1.644	1.619	3.216	3.516
thickness H in mm	0.978	0.719	1.042	0.990
density in sea water	1.83	1.87	2.01	1.98
estimated volume in mm ³	1.38	0.99	5.64	6.41
critical shear stress	0.043	0.042	0.048	0.048
critical shear velocity cm/sec	2.3	2.4	2.6	2.6
shape entropy	0.98	0.95	0.91	0.89
settling velocity cm/sec	9.39	8.09	12.79	11.65