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Abstract

Some 350 flume tests were conducted with shells of pelecypods, *Dinocardium robustum* Solander and *Anadara braziliana* Lamarck, to determine how physical characteristics of shells affect their ease of movement when partially submerged in swash water on a beach. The distance moved by a shell in the flume varied inversely with the square root of the effective density. The force required to move the shells was directly proportional to the normal component of the weight. Air entrapped beneath shells decreased the normal component of the shell weight so that they could be moved by a smaller force. Shells with holes bored in them did not entrap air and traveled relatively small distances in the flume.

Contents

Introduction

Shells are commonly used by the paleoecologist to reconstruct ancient environments. Before basic conclusions can be inferred from shell distribution, however, it is necessary to determine whether shells are indigenous or exotic, and to estimate the degree of sorting. Basic information concerning factors affecting shell transport may be obtained by studying shell movement in controlled flume experiments.

Menard and Boucot (1951) studied the current velocities necessary to move terebratuloid brachiopod shells in a laboratory flume and found the movement of shells to be primarily controlled by the relative ease of movement of the sub-adjacent bed material. Shape, size, effective density, and ornamentation were also found to influence the velocity required to move a shell. Johnson (1957) performed flume experiments which indicated that current-scouring induced by the presence of clam shells resting on a movable substrate is an effective mechanism for their burial.

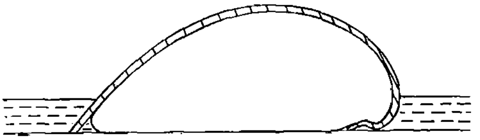
The previously mentioned experiments were concerned with the movement of shells completely submerged. The present authors became interested in factors controlling the movement of shells after their initial deposition on a beach. Deposition of a shell on a beach usually does not end its exposure to further transport by water because succeeding swashes and higher tides continue to move the shell. Johnson (1957) conducted experiments in which single valves of pelecypods were set out on a muddy-sand beach just above the low tide mark. When the area was revisited at the following low tide, Johnson found that 40 per cent of the shells had been moved from their original site by currents. Nearly 90 per cent of the shells moved had been those that had originally been placed with the concave side up. Many of the shells which had been placed with the concave side down had been partially or almost completely buried in the muddy-sand. Martin-Kaye (1951) and Lever (1958) have investigated the interesting phenomenon that one valve of a pelecypod is sometimes much more common on a beach than the other. Shells with the concave side down have water beneath when submerged but have air beneath when exposed on a beach (Figure 1). In preliminary flume experiments it was observed that the air beneath a shell tended to make it more buoyant and to increase the ease by which it was moved by water currents. This effect of air entrapped beneath a clam shell on its further transport on a beach has not, so far as the authors know, been previously reported in the literature. The experiments reported in this paper were undertaken in order to determine the manner in which physical characteristics of shells affect buoyancy and the ease of shell movement by currents.

ACKNOWLEDGMENT

The writers are indebted to Dr. M. King Hubbert who criticized the manuscript and made many valuable suggestions. The manuscript has been read by Dr. C. Oppenheimer, and Mr. Charles Wise, who also supplied information concerning the distribution of shells on Mustang Island. Dr. John T. Conover assisted in field work. Mr. John Stokes was helpful in discussions on fluid dynamics. The collecting of shells on the Yucatan Peninsula was made possible through a National Science Foundation Grant, NSF G 8902.

Shell Buoyancy

One of the oldest physical principles is that of Archimedes, which states that the buoyant force on immersed bodies is equal to the weight of displaced liquid. This princi-



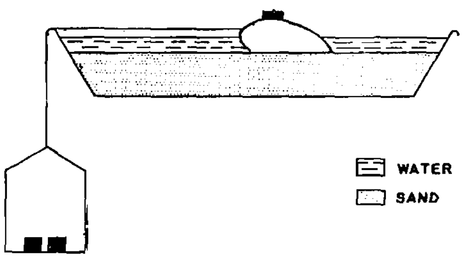


FIG. 1. Position of shell partially submerged, concave side down.

FIG. 2. Experimental arrangement used for determining the horizontal force required to move shells partially submerged in water.

ple has important application to the present study of shell movement in the beach environment. When a disarticulated clam shell is deposited on a beach with the concave side down, the concavity fills with air after water drains from around and under the shell. If the shell is again exposed to swash water, it is not only buoyed up by the water displaced by the shell, but also by water displaced by the air entrapped beneath the shell.

The buoyancy of the air in a shell partially submerged (as in Figure 1) may be determined with the following procedure. A shell is first weighed in air (A) and then when partially immersed in water (B). Weighings in water may be made by placing valve concave side down on a balance pan suspended in water. The shell is then turned concave side up and partially filled with water to the same water line previously reached by water during the shell weighing. The additional volume of water required to completely fill the shell is now measured using a burette. This volume of water is converted to grams (C). A hole is drilled through the shell and the shell reweighed in air (A_d) and then reweighed when immersed in water (B_d) to the same water line as before. With the drilled hole in the shell no air is entrapped. The difference between the weight of the shell in air (A_d) and in water (B_d) represents the weight of water (D) displaced by the part of shell wall below water ($A_d - B_d = D$). If the air entrapped beneath the shell creates a buoyant force equal to the weight of water displaced, then,

$$A - B - D = C \tag{1}$$

where A is the weight of shell in air, B is the weight of shell when partially submerged in water with air entrapped, C is the weight of water displaced by entrapped air, and D is the weight of water displaced by the submerged shell wall.

Results of using the above procedure on two shells of *D. robustum* are given in Table 1. The small differences between A − B − D (column 4) and C (column 5) are considered to be within the accuracy of the method.

Although a shell out of water weighs more than when it is completely immersed, its weight is least when buoyed by entrapped air. For example, a shell of *D. robustum* which weighed 49.9 gm in air, and 31.7 gm when completely immersed without air entrapped, weighed only 26.0 gm when partially submersed concave side down in water 7 mm deep.

Forces Required to Move Shells

The force (F) required to move an object over a surface is approximately proportional to the load; or

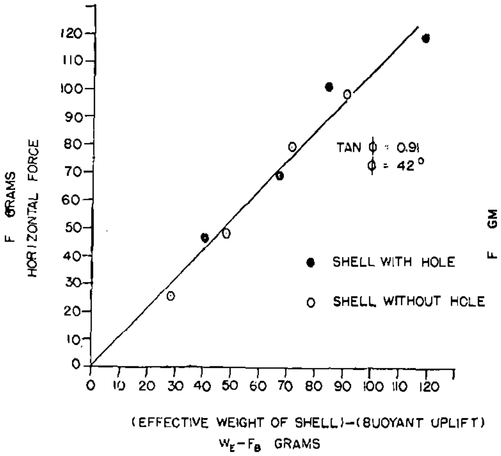
$$F = fF' \tag{2}$$

where f is the coefficient of sliding friction, and F′ is the force pressing the sliding body against, and perpendicular to, the sliding surface (Stewart, 1944, p. 131).

TABLE 1

Comparison of amount of water displaced by entrapped air under *Dinocardium robustum* shells determined gravimetrically and volumetrically

A Weight in air gm	B Weight in 7 mm of water without hole gm	D Water displaced by shell wall gm	A-B-D Water displaced by air entrapped gm	C Water displaced by air estimated volumetrically gm
54.2	21.5	1.3	31.4	33.7
73.1	43.0	2.0	28.1	32.4



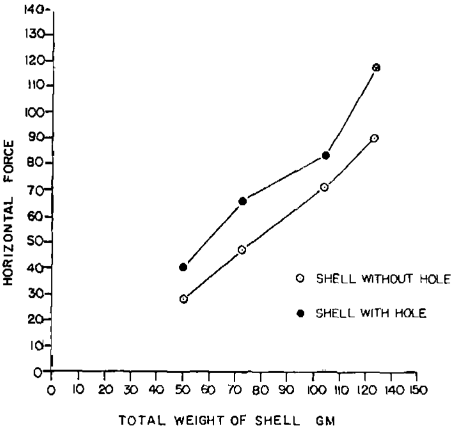


FIG. 3. Horizontal force F required to move a *Dinocardium robustum* valve partially submersed in 0.7 cm of water as a function of the normal component of shell weight ($W_e - F_b$), where W_e is the effective weight and F_b is the buoyant force directed upward caused by entrapped air. The normal weight of the valve was varied by placing brass weights on top of the valve. Data are included from valves with and without holes.

FIG. 4. Horizontal force F required to move a *Dinocardium robustum* valve partially submersed in 0.7 cm of water as a function of the weight of the shell in air. Data and symbols as in Figure 3.

The air under a shell, in addition to the portion of the shell submersed, produces an upward buoyant force so that

$$F' = W_e - F_b \qquad (3)$$

where W_e is the effective weight of the partially submersed shell (weight of shell in air less the buoyant uplift due to the water displaced by the portion of shell submerged) and F_b the buoyant uplift due to the water displaced by air. Substituting this in equation (1) then gives

$$F = f\,(W_e - F_b) \qquad (4)$$

If a shell should have a hole in the top, there would be no buoyant uplift F_b due to air entrapment, and the corresponding equation would be

$$F = fW_e \qquad (5)$$

Thus, theoretical considerations predict that the force required to move a shell when plotted graphically against the quantity ($W_e - F_b$) should fall along a straight line passing through the origin with slope tan ($\tan \phi = f$) (see Hubbert and Rubey, 1959, pp. 159–160, for discussion of this principal applied to earth movements). The force required to move a shell with a hole having no buoyancy due to entrapped air when plotted against the quantity W_e should have the same slope as that obtained by plotting force against ($W_e - F_b$), if the coefficient of friction is the same in both cases. Both graphs should pass through the origin and should therefore coincide.

The theory was tested by measuring the force necessary to move shells placed concave down on sand in a pan containing 7 mm of water (Figure 2). Only one shell was used in the experiment in order to eliminate such variables as shape and size. The shell-weight was varied by placing brass weights on the shell. Experiments were first performed with the shell intact and then with a hole drilled through the top and the data plotted in Figure 3. The superposition of the data from these experiments is considered direct confirmation that the coefficient of friction is the same for the shells with and without entrapped air (f = 0.91). The linear relationship in Figure 3 is evidence that the force required to move the shells is directly proportional to the normal component of the weight of the shells.

When the force required to move shells is plotted graphically against the weight of the shells in air (Figure 4), it becomes readily apparent that the buoyancy of the entrapped air allowed the shells to be moved by a smaller force.

Experiments on Shell Transfer in a Flume

Description and Operation of the Flume

Experiments were conducted in a wooden flume having overall dimensions of 41 cm in width and 183 cm in length (Figure 5). An internal flume, or runway, 10 cm wide and 85 cm long was constructed inside the larger flume. The internal flume was necessary in order to obtain desired high velocities with the available water supply. Holes drilled into the exit end of the flume were used to regulate water level. The water level was adjusted by corking certain holes and leaving others open.

Sand from the water's edge one mile south of South Pier on the Mustang Island beach facing the Gulf of Mexico was used in all experiments. The sand is well sorted and typical of beach sand in this area (Figure 6). About 4 per cent of the sand consisted of shell fragments; the balance was quartz sand mixed with a small amount of heavy minerals. During experiments the sand bed was maintained horizontally. A constant bed level was maintained by adjusting the bed and adding new sand before each experiment whenever necessary. The sand layer was approximately 12 cm thick. About one millimeter of scour occurred from around shells during the short duration of each flume experiment. No shells became buried during the trials, but the bed was lowered 10 mm beneath a *D. robustum* valve when the water flow was continued for 20 minutes.

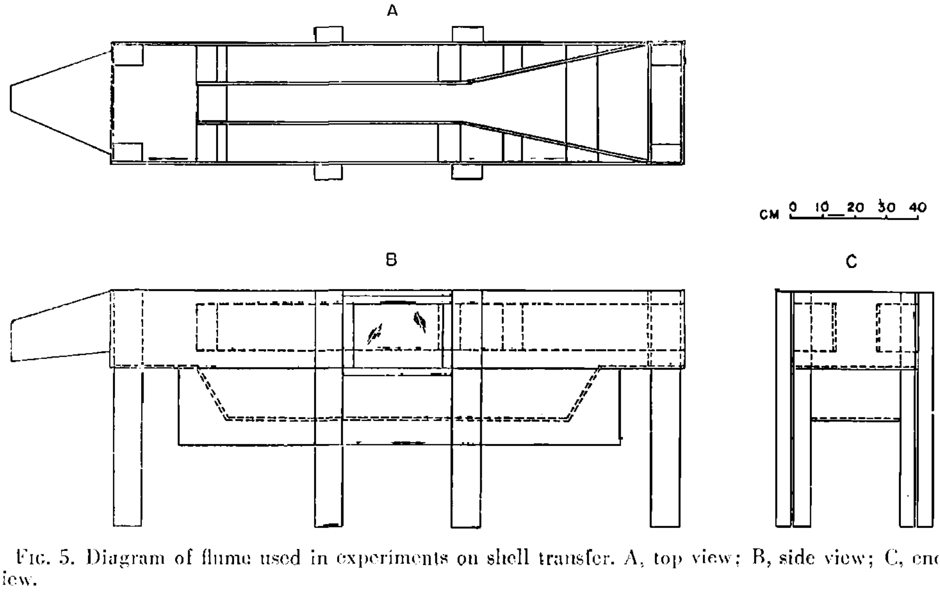
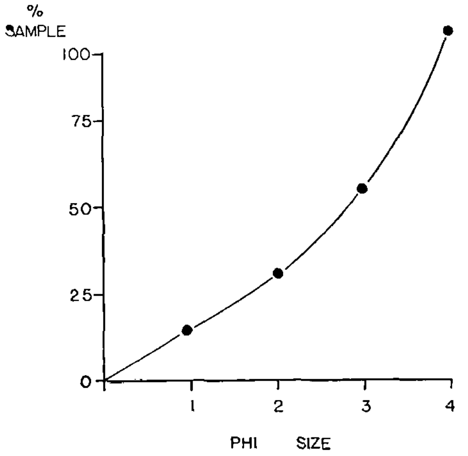


FIG. 5. Diagram of flume used in experiments on shell transfer. A, top view; B, side view; C, end view.



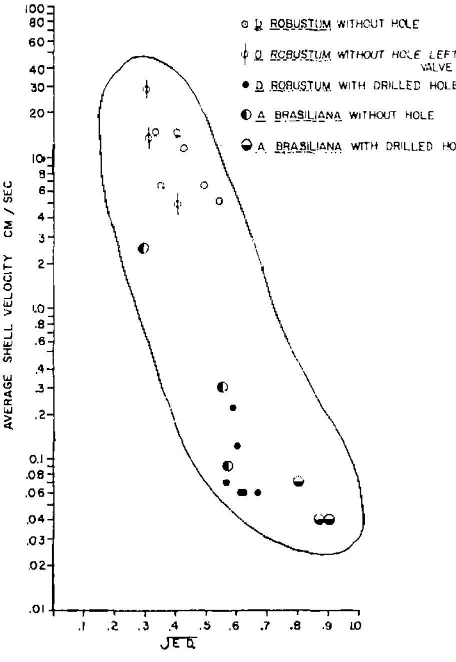


FIG. 6. Size distribution of sand used in flume experiments on shell transfer. Ordinate Phi is — $\log_2$ mean diameter.

FIG. 7. Average shell velocity obtained for each series of flume experiments as a function of the square root of the effective density (ED) of shell upon which the experiment was performed. The effective density was calculated by dividing the weight of the shell when immersed in 0.7 cm of water (W_e) by the volume (V) of the shell. The shell concavity as well as the solid part of the shell is included in the shell volume (V).

Water from a hose was run into a well at the head of the flume. The overflow from the well coursed down the flume and ran out through the holes in the foot of the flume. Water level during the experiments was maintained at 7 mm. Water velocity was held constant at 50 cm/sec. by periodically measuring the rate of discharge and, when necessary, adjusting inflow. The mean current velocity was then calculated by dividing the discharge by the cross-sectional area of flow in the runway. The current velocity was also determined by measuring the velocity of bits of wood placed in the runway. Well water with a salinity of six parts per thousand from Mustang Island was used in the experiments. The air and water temperatures during the experiments were approximately 30° C.

Two pelecypod species were used. *Dinocardium robustum* Solander is a large cockle shell found in abundance washed up on beaches along the Texas coast. Specimens reach three to four inches in size, are oval, inflated, and have many ribs. The species is figured by Abbott (1954, Plate 32, Figure a).

Anadara brasiliana Lamarck is a ribbed ark shell about 1–2½ inches in length. The left valve overlaps the right along the postero-ventral margin. The species is figured by Abbott (1954, Plate 27, Figure y). Ark shells with a shape similar to that of *A. brasiliana* are almost world-wide in occurrence. The family Arcacea extends from the Ordovician to the Recent (Moore, Lalicker, and Fischer, 1952, p. 411).

After the standard condition of water depth and velocity was established in the flume, a pelecypod valve was placed at a designated place near the head of the flume. All valves used in the experiments were oriented the same way, *i.e.*, convex upward with the beak pointing upstream. The time for the shell to travel 80 cm from the head to the end of the runway was determined with a stopwatch. All experiments were terminated after one minute, and the data reported as distance in centimeters moved by a shell in one minute. The distance traveled by shells which moved more than 80 cm in one minute was estimated by extrapolation. Each series of experiments was repeated a minimum of 10 times. The shells of *A. brasiliana* had a tendency to overturn (15 shells overturned in 110 trials). As hydraulic factors affecting shells in a concave upward position are different than shells in a convex upward position, the velocity data from overturned specimens were excluded in calculating average velocities.

Distances moved by eight specimens of *D. robustum* and three specimens of *A. brasiliana* were measured. These values had air trapped beneath them. Holes were then drilled in each shell and the travel distance in the flume measured. The average distances travelled by the shells are presented in Table 2. Four speciments of *A. brasiliana* with snail-drilled holes were also tested in the flume.

Results and Discussion of Flume Experiments

Flume tests performed by Menard and Boucot (1951) showed that the initial movement of terebratuloid brachiopods depends primarily on the effective density and secondarily on the shape and size of the shell. In the experiments performed by Menard and Boucot, the water velocity required to initiate shell movement was measured. In the present series of experiments, water velocity was held constant (50 cm/sec.) and the distance the shell moved in a given time (1 min.) was measured. The results obtained in each procedure should be related, *i.e.*, if shell A is moved by a smaller current than shell B, shell A will also move farther than shell B when exposed to a current capable of moving one or both shells.

Menard and Boucot (1951) found that initial movement of submerged articulated terebratuloid brachiopods depends primarily on their effective densities. Effective density also seems to be the principal factor affecting transport of partly immersed disarticulated pelecypod values of *D. robustum* and *A. brasiliana*; the distance traveled was related inversely to the square root of the effective density (Figure 7).

Density is defined as the ratio of the mass of a body to its volume. If the body is not of uniform density this definition of density gives an average value. Effective density may be defined by

$$\rho_e = \rho - \rho_w \qquad (6)$$

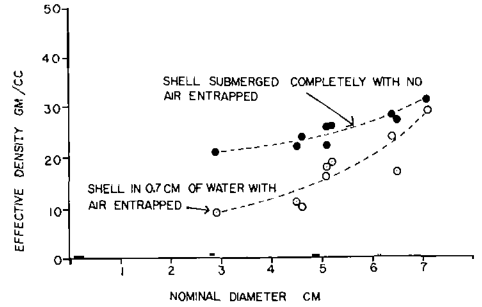
where ρ is the mean density of the mass contained in the volume (V) and ρ_w is the density of water. The volume (V) includes not only shell volume but also volume of the shell cavity in the case of articulated shells (Menard and Boucot, 1951, p. 134). In the present work in which disarticulated shells were studied, the shell concavity was included in total volume when calculating effective density.

The effective density of shells completely covered with water and without entrapped air increases slightly with increase in shell size (Figure 8). This is because the shape of the shell changes little with increase in size, but the shell wall becomes thicker (Figure 9). When the shells of different sizes were partially immersed in 7 mm of water, the effective density of the shells increased relatively rapidly with increase in size (Figure 8). This is because the small shells displaced more water relative to their mass than the

TABLE 2

Physical characteristics and flume behavior of valves

Species and type of valve	Height cm	Length cm	Thickness cm	Weight gm	Sphericity	Normal diameter cm	Hole diameter cm	Cup volume cc	Average wall thickness cm	Weight in 7 mm water gm	Effective density in 7 mm water gm/cc	Average shell velocity cm/sec.	Number of trials
Dinocardium robustum													
Left valve	9.3	8.0	3.4	48.4	0.68	6.4	none	91.2	0.25	13.4	0.12	6.6	25
Left valve	9.3	8.0	3.4	47.0	0.68	6.4	1.3	91.2	0.25	45.1	0.42	.06	15
Left valve	7.2	6.7	2.8	19.1	0.72	5.1	none	46.0	0.20	8.5	0.16	14.3	24
Left valve	7.2	6.7	2.8	18.4	0.72	5.1	2.0	46.0	0.20	18.5	0.36	.12	15
Left valve	6.2	5.8	2.5	12.8	0.73	4.5	none	31.0	0.19	3.7	0.11	14.8	15
Left valve	6.2	5.8	2.5	12.7	0.73	4.5	0.9	31.0	0.19	11.5	0.32	.07	15
Right valve	6.3	8.5	2.6	12.9	0.73	4.6	none	29.0	0.19	3.2	0.10	13.6	10
Left valve	7.3	6.7	2.8	23.3	0.71	5.2	none	46.5	0.22	10.5	0.19	11.6	14
Left valve	7.3	6.7	2.8	23.2	0.71	5.2	0.9	46.5	0.22	20.7	0.38	.06	15
Left valve	7.1	6.8	2.8	25.0	0.72	5.1	none	51.0	0.22	11.0	0.18	11.6	15
Left valve	7.1	6.8	2.8	24.8	0.72	5.1	0.9	51.0	0.22	22.6	0.38	.06	15
Left valve	9.2	8.3	3.5	49.9	0.71	6.4	none	90.0	0.25	26.0	0.24	6.3	15
Left valve	9.2	8.3	3.5	49.8	0.71	6.4	0.9	90.0	0.25	47.1	0.44	.06	15
Right valve	9.4	8.4	3.6	54.2	0.70	6.5	none	105.0	0.25	21.5	0.17	4.8	10
Left valve	9.7	9.2	3.9	73.1	0.72	7.1	none	120.0	0.32	43.0	0.29	5.1	10
Right valve	4.0	3.8	1.6	3.8	0.73	2.9	none	9.0	0.13	0.9	0.09	28.6	10
Right valve	4.0	3.8	1.6	3.8	0.73	2.9	0.5	9.0	0.13	3.6	0.35	.24	10
Anadara brasiliana													
Left valve	4.1	4.0	1.9	12.3	0.77	3.2	none	10.5	0.28	4.4	0.30	0.3	6
Left valve	4.1	4.0	1.9	12.2	0.77	3.2	0.5	10.5	0.28	11.3	0.75	.04	10
Left valve	3.5	3.5	1.5	6.3	0.75	2.6	none	5.0	0.24	2.3	0.32	0.9	8
Left valve	3.5	3.5	1.5	6.2	0.75	2.6	0.5	5.0	0.24	5.9	0.81	.04	10
Left valve	3.6	3.5	1.5	3.2	0.74	2.7	none	3.0	0.20	0.3	0.08	2.5	8
Left valve	3.6	3.5	1.5	3.1	0.74	2.7	0.5	3.0	0.20	2.6	0.64	.07	10
Anadara brasiliana (with snail bored hole)													
Left valve	4.0	4.0	1.7	9.5	0.75	3.0	0.20	9.4	0.25	2.7–8.3	0.21–0.65?	0.4	10
Left valve	2.8	2.7	1.0	2.6	0.71	2.0	0.15	2.8	0.19	1.7	0.14?	13.0	10
Left valve	3.2	3.3	1.4	5.2	0.74	2.4	0.20	5.4	0.23	3.4	0.91?	0.2	10
Left valve	1.7	1.7	0.7	0.6	0.73	1.2	0.12	0.8	0.15	0.2	0.19?	6.0	10



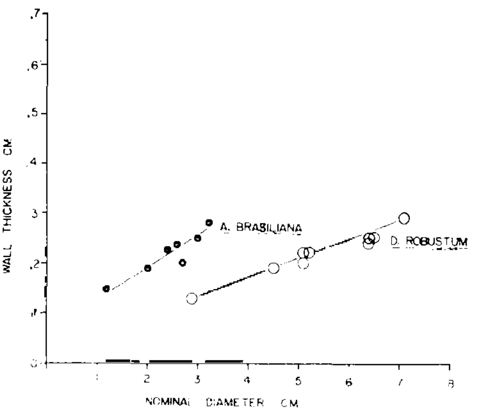


FIG. 8. Effective density of *Dinocardium robustum* valves as a function of the nominal diameter. The nominal diameter is calculated by taking the cube root of the product of the length, width, and thickness of each shell. Shell length was measured along the longest rib in the central portion of the shell. The width was considered the greatest distance between the anterior and posterior margins measured in the plane of commissure and normal to the height. The height is the maximum dimension of the individual valve measured perpendicular to the plane of commissure; height as used here is one-half height of closed articulated shell.

FIG. 9. Wall thickness of shells of *Anadara brasiliana* and *Dinocardium robustum* as a function of nominal diameter. Wall thickness is a term used here to denote the distance between the inner and outer surface of a single valve. Wall thickness was measured with a micrometer at three places along a line parallel to the ventral margin and about one-third the distance from the ventral to dorsal margin; these measurements were averaged.

large shells. If, as indicated in Figure 7, effective density is a major factor in shell transport, and shell size has a greater effect on effective density when shells are only partly immersed, it follows that shells are probably more readily sorted according to size when partially immersed. This suggests that shells are more readily sorted according to size in the beach environment than when completely submerged.

The effect of the air entrapped beneath clam shells in increasing ease of transport becomes very apparent when the distances traveled by shells without air (having a hole bored in shell) are compared with distances traveled by shells of the same size with air entrapped beneath them (Figure 10).

Shells of *A. brasiliana* had higher effective densities than similar sized shells of *D. robustum* because of the thicker shells of the former species (Figure 9). The effect of the higher effective density in decreasing the relative distance transported by *A. brasiliana* is readily seen in Figure 10.

The intercept sphericity (defined by Krumbein, 1941) was calculated for each shell and found to fall between 0.6–0.8. The small differences in the shapes of shells used in the experiments had no measurable effect on shell transport. The simple ornamentation on the species tested had no apparent influence on ease of shell movement.

BEACH EXPERIMENTS

In order to see if the behavior of shells in the flume was representative of their behavior on the beach when exposed to swash water, a series of tests was run on the beach. Two pairs of *D. robustum* shells which had previously been tested in the flume were placed near the water's edge. The left valve of each pair contained a hole drilled through the shell. The valves without holes moved a considerable distance inland with each

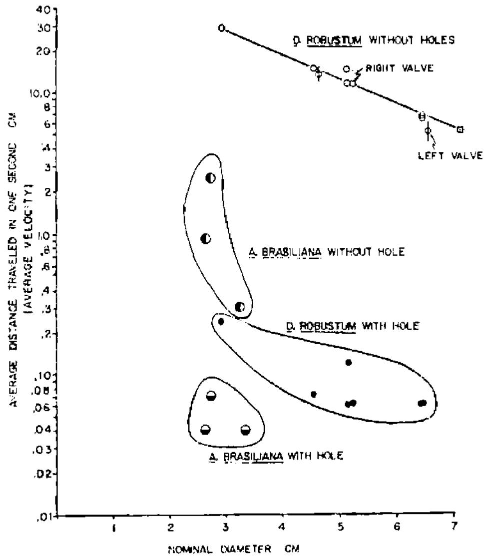


FIG. 10. Average velocity of shells of *Anadara brasiliana* and *Dinocardium robustum* in flume experiments as a function of nominal diameter.

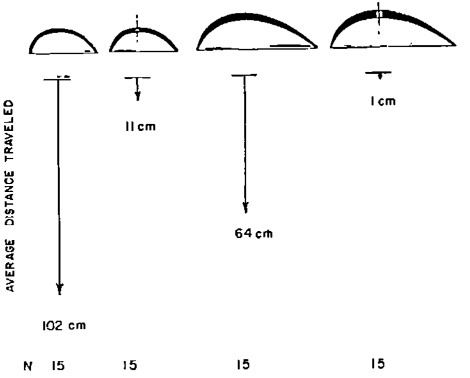


FIG. 11. Distances traveled by *Dinocardium robustum* valves placed at the waters edge and transported shoreward by one, or at most, two swashes. Position of shells and condition of shell (with or without drilled hole) is indicated by shell outlines. Air was entrapped under shells without holes.

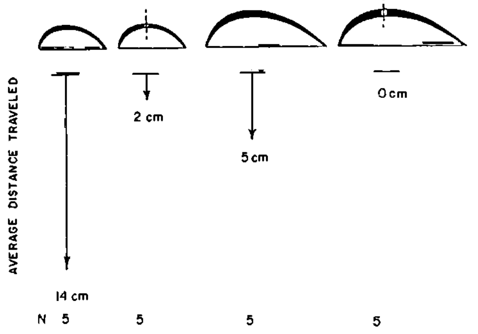


FIG. 12. Distances traveled by *Dinocardium robustum* valves placed below low water level during one minute. Same shells as in Figure 10. No air was entrapped beneath valves.

swash, but the valves with holes moved only a short distance, or not at all (Figure 11).

The experiments were repeated in deeper water below the swash area, so that the shells were continuously submerged. Air was allowed to escape completely from beneath the shells before they were placed concave downward on the sand surface. The shells without holes moved farther than the shells with holes (Figure 12). The relatively short distances traveled by the shells without holes were not the result of buoyancy, as was the case with partially submerged shells, but because the hole permitted equalization of the pressure beneath and above the shell, thus deminishing the "lift" due to a decrease in pressure on the upper side caused by the moving water. For discussion of Bernoulli's theorum, which concerns changes of pressure with change of speed, see

Stewart, 1944, p. 181, or standard text on physics. The lifting effect on those valves without holes decreased the normal component of the effective weight of the shell so that it could be moved by slower water currents.

Shell Orientation in Moving Water

Final orientation of a shell which has been exposed to water current reflects current direction. Because of this the process by which shells are oriented is of interest to the paleoecologist. Shells were oriented at the beginning of each flume test with the shell beak pointing upstream. Shells with holes did not move far from where they were placed, and the shells maintained their initial orientation. Shells with air entrapped, on the other hand, traveled considerable distances; these shells were oriented differently at the end of the tests than at the beginning. Left valves rotated counter-clockwise, whereas right valves rotated clockwise. This is opposite the direction of rotation of left and right shells of *Donax vittatus* observed by Lever (1958). The reason for this is that the left valve of *Donax vittatus* more closely resembles in shape and distribution of mass the right valves of *Dinocardium robustum* and *Anadara brasiliana* than it does the left valves. Both in the flume and beach experiments the two species studied became oriented with the posterior end of the shell downstream, and with the beaks of the left valves 90° counter-clockwise from the current direction, and the beaks of the right valves 90° clockwise (Figure 13). The final orientation was probably due, in part, to a tendency of each

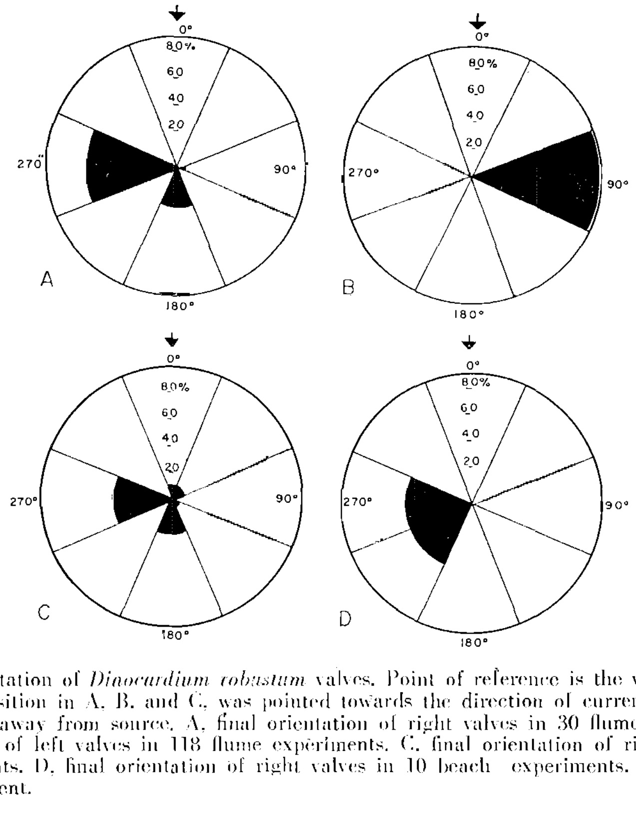


FIG. 13. Orientation of *Dinocardium robustum* valves. Point of reference is the valve beak which in the initial position in A, B, and C, was pointed towards the direction of current source, and in D, was pointed away from source. A, final orientation of right valves in 30 flume experiments. B, final orientation of left valves in 118 flume experiments. C, final orientation of right valves in 20 beach experiments. D, final orientation of right valves in 10 beach experiments. Arrow indicates direction of current.

shell to present its most streamlined silhouette to the current and, in part, to the distribution of mass in the shell. The anterior of the shell, because of its greater thickness, is heavier than the posterior and acts as an anchor while the posterior part trails downstream.

Orientation observations were restricted to shells with air entrapped beneath them. As data are not available showing how these shells become oriented when completely submerged without air entrapped, it is not possible to determine whether the presence of air beneath the shell affected the final orientation. However, air entrapped beneath clamshells probably plays a major part in determining their final orientation. For example, air beneath *D. robustum* valves in a centimeter or more of water tends to lift the umbo of the shell. Observations at the beach showed that when this occurs the umbo of the shell swings towards the beach with a gentle incoming swash, and away from the beach with a receding swash, and sometimes the valves are overturned (Figure 14).

Water movement on the beach is infinitely more complex than in the flume where, for example, the water moved only in one direction. On the beach the swash flows in two principal directions, first towards shore and then away from it, but usually it does not follow the same path in and out. Successive swashes do not always come from the same direction, nor are they evenly spaced. The shells during the beach test became oriented in more or less the same manner as when they were in the flume, in part, because they were exposed only to the incoming swash and, in part, because the water velocities were not high. At high velocities, such as those observed by the senior author after a hurricane, shells roll end over end in the swash zone. An excellent discussion on the effect of swash moving obliquely up and down the beach on shell orientation and sorting is given by Lever (1958).

Behavior of Shells Progressively Covered by Water

Buoyant force increases as shells are progressively covered by water because more and more water is displaced. Observations were made of shells of *D. robustum* and *A. brasiliana* progressively covered by water both in the swash zone and in the laboratory, where shells were placed inside beakers which were then slowly filled with water. Air escaped from beneath the shells when they were about half covered by water. Air escape culminated with the release of a large bubble from beneath the dorsal edge of the shell. The plane of commissure of shells of *D. robustum* formed an angle of about 80° with the horizontal at the time the large bubble was released. Many shells of *D. robustum* overturned apparently due to the pushing action of the released bubble. Those shells that did not overturn, but returned to the bottom after the release of the large bubble of air retained some of the original air beneath them. No further air was released with further increase in water level. The volume of air trapped beneath two *D. robustum* shells was measured after they settled to the bottom. One shell contained 19 cc or 18.2 per cent of the original volume of entrapped air; the other shell contained 8 cc or 16.3 per cent of the original entrapped air. The volume of air retained beneath the shell is sufficient to materially increase the shell's buoyancy. Shells of *A. brasiliana*, which are heavier than shells of *D. robustum* of the same size, did not overturn.

The importance of the buoyant uplift of entrapped air in overturning valves may be reflected in the relative proportions of values of *D. robustum* and *A. brasiliana* deposited on a beach. In a collection of *D. robustum* shells cast upon the beach of Mustang Island

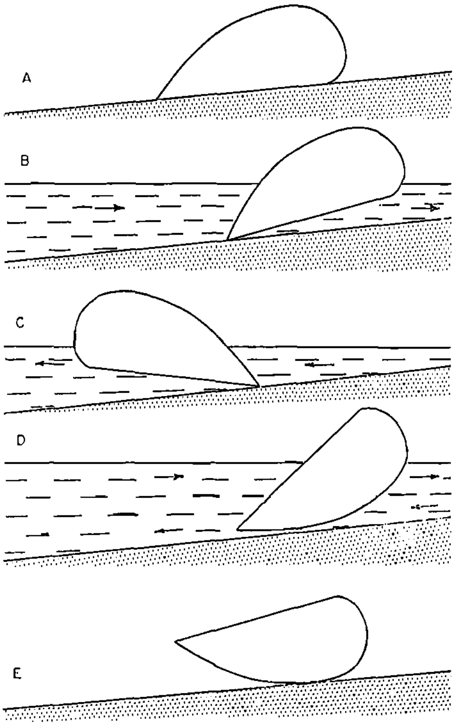


Fig. 14. Behavior of *Dinocardium robustum* shell observed on the beach of Mustang Island, Texas. A, original position and attitude of shell above waters edge. B, encompassed by incoming swash with air entrapped beneath the shell raising the beak. C, outgoing swash turns shell with ventral edge as pivot. D, incoming swash overturns shell. E, final position and attitude of shell on beach.

within a 24 hour period 65 per cent (82) were concave upward. On the other hand, shells of *A. brasiliana* are usually found convex upward, *e.g.*, in a collection of 95 shells made along the water's edge of Mustang Island, 85 per cent were found convex upward.

In deeper water both species usually occur in a convex upward position. In 10 trials in water 20 cm deep, two specimens of *D. robustum* placed concave side up on the sand surface averaged only seven seconds in this position before turning over. When the procedure was reversed and the specimens were placed on the sand convex upward, all valves were in the same position at the end of one minute's observation. However, in the interim each specimen had turned completely over (360°) an average of one time. The valves remained more or less in the same place during the observations. The fact that single pelecypod shells are more stable with the concave side down and are usually found in that position is well known (Shrock, 1948, pp. 313–320). The present observation suggests that single valves acted upon by currents turn over and over, remaining a short time in the concave upward position and a considerably longer time in the concave downward position. At any given time more valves would be in the concave down position than in the concave up position.

The Effect of Naturally Bored Holes on Shell Transport

Holes in shells are formed in nature by boring snails, boring sponges, boring algae, boring fungi, worms, and by abrasion or breakage. The per cent of shells with holes is sometimes a considerable part of the total shell accumulation, *e.g.*, 88 per cent of dead shells belonging to the pelecypod *Spissula elliptica* collected along some coasts have been bored by the snail *Natica alderi* (Twenhofel and Schrock, 1935, p. 359). In conjunction with the present study the authors tabulated the number and probable cause of holes in a collection of shells from a Gulf of Mexico beach near Progreso, Yucatan Peninsula, Mexico (Table 3). Snail-bored shells of brachiopods have been reported from as far back as the early Paleozoic (Bucher, 1938). Boring sponges have an equally long range.

Holes made by boring sponges, algae, fungi, worms, and some snails are extremely small. No escape of air was evident when shells with considerable sponge borings were emersed convex upward under water. Air readily escaped from larger holes caused by abrasion or breakage but small holes apparently do not allow passage of air.

Snail-drilled holes vary considerably in diameter and position on the drilled shell. Air does not readily escape from snail-drilled holes having a small diameter. The position of a snail-drilled hole also affects the volume of air entrapped beneath the shell, because air above the hole is retained. For example, the volume of air retained beneath several snail-drilled shells of *A. brasiliana* was measured and found to vary from about 39 to 59 per cent of the internal volume of the shell (Table 4). Velocities obtained in flume experiments using snail-drilled shells were quite variable and higher than obtained with artificially drilled holes, probably because of air retained beneath the snail-drilled shells.

It is conceivable that shells with holes might accumulate in one place on a beach and shells of similar size without holes in another. Bucher (1938) found many snail-drilled shells of the brachiopod *Dalmanella meeki* (Miller) in a thin shale of Upper Cincinnatian age, although snail-drilled shells were rare elsewhere. This may have been the result of differential sorting.

Conclusions

1. The force required to move shells is directly proportional to the normal component of the weight of the shell. Air entrapped beneath a clamshell decreases the normal component of the shell weight so that it can be moved by a smaller force.

TABLE 3

Statistics on the number and cause of holes in two common species of pelecypods collected from a beach near Progreso, a seaport town on the Yucatan Peninsula, Mexico

Species	Total number collected	Percent with hole	Percent perforated by sponge	Percent drilled by snail	Percent with hole eroded
Arca zebra	156	66.6	56.2	1.7	8.7
Chione cancellata	118	27.5	13.2	14.3	0

TABLE 4

Volume of air entrapped beneath valves of *A. braziliana* containing holes drilled by snails

Type of valve	Hole diameter cm	Hole position	Cup volume cc	Air entrapped cc	Approximate percent of original air remaining under shell
Left	0.20	umbo	9.4	5.6	59.5
Left	0.15	umbo	2.8	1.0	39.7
Left	0.20	umbo	5.4	2.1	39.0
Left	0.12	umbo	0.8	1.0	.....