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EXPERIMENTS ON THE MOVEMENT OF SHELLS BY WATER[1]

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ABSTRACT. Experiments in a laboratory flume indicate that the current velocity necessary to move terebratuloid brachiopod shells is only about one tenth of the velocity required to move pebbles of the same size. Movement of shells is controlled primarily by the relative ease of movement of the subjacent bed material; a shell may move over a bed of gravel but sink into a bed of sand because of the rapid removal of adjacent sand grains by scouring.

Shape, size, effective density, and ornamentation influence the competent velocity of a shell. Competent velocity increases with sphericity.

INTRODUCTION

PALEOECOLOGISTS are aware that a fossil assemblage of shells does not necessarily represent a community assemblage preserved in place. Instead, the fossil assemblage may constitute a diverse assortment of shells brought together by physical agencies, ordinarily after death, and then buried. Moving water is one of the most important agents affecting the transportation and sorting of unattached dead shells or those otherwise incapable of independent movement. The writers know of no experimental observations on the current velocities required to initiate the movement of shells, nor of the effect of transportation on an assemblage. For these reasons it seemed desirable to make such observations when a hydraulic flume temporarily became available at the Woods Hole Oceanographic Institution in the fall of 1948.

During the experiments, the relations between the variables affecting the movement of the shells seemed to be simple; so no exhaustive study was attempted. Subsequent analysis of the observations revealed that the relations were unexpectedly complex. It is apparent now that many more experiments will be required before the initial movement of shells can be explained completely or predicted. Consequently, the present conclusions cannot be offered as more than first approximations. They are submitted at this time because neither of the writers is likely to have access to a hydraulic flume in the near future.

This paper presents some results of the tests, as well as a brief consideration of their significance with regard to paleoecology. The writers wish to express their appreciation to

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The experiments were done in a wooden flume one foot wide and 6 feet long, with a glass observation panel in one side. In 26 tests, a recess in the central 3 feet of the flume was filled with medium-fine sand (diameter 0.36 mm.) to the level of the flume bottom; in one test, the recess was filled with a gravel composed of grains 2-5 mm. in diameter. The bottom of the flume had a fixed slope of 0.002 during all these tests. In a typical run, a tailgate was fixed in place in order to produce the desired depth of flow in the flume; several shells were placed on the smoothed sand bottom; and the flume was filled with fresh water at a rate slow enough so that neither the shells nor the sand were disturbed; then the flow of water in the flume gradually was increased until one of the shells or the sand moved. The depth of water in the flume and the discharge of the water were measured when movement occurred. The mean current velocity was then calculated by dividing the discharge by the cross-sectional area of the flow within the flume.

Some 27 runs were executed, and 39 individual dry shells, representing 9 species of terebratuloid brachiopods, were tested. Observations were made on the current velocity competent to move the shells, the nature of the movement, scour of sand around the shells, and the orientation of the shells during and after movement. The length, width, thickness, weight, nominal diameter, and sphericity of the shells used in these runs, and the results of the tests are shown in tables 1 and 2.

The velocity required to move a brachiopod shell lying free on a substratum of sand depends on the shell properties of size, effective density, shape, and ornamentation, and on whether the valves are hinged together or separated. All these variables except ornamentation are considered in the present tests. The most important variable governing the initial movement of shells, however, appears to be the relative ease of movement of the shell and the underlying sand grains. Thus, a certain current may roll a shell over a gravel bottom with ease, but be incapable of moving it over sand because the sand moves more readily than the shell. If the sand moves first, a scour is formed around the shell, which may be dropped into it and buried by moving sand. Because of the importance of the relative ease of motion of sand and shells, the detailed discussion of the tests is divided into two sections, one concerned with shells which move more easily than sand, and the other concerned with shells which move less easily than sand.

WHOLE SHELLS WHICH ARE EASIER TO MOVE THAN THE UNDERLYING SAND

Unattached shells are clastic particles in the same sense as grains of sand or gravel, and hence the factors governing their movement are the same. As the movement of sand and gravel has been studied in great detail whereas the movement of shells has not, it seems profitable to consider sediment movement before turning to shell movement.

The characteristics of a grain which influence its initial movement on the bed of a watercourse are the size, density, and shape. Hydraulic engineers generally agree that the current velocity competent to move coarse sand and pebbles is proportional to the square root of the diameter of the grains (Hjulstrom, 1935); the same proportionality probably holds for all larger sizes of gravel (Menard, 1949). The competent velocity commonly is thought to be proportional to the square root of the effective density (weight per unit volume if the grains are immersed in water). As to the shape, Krumbein (1942) finds that the more spherical a grain of gravel, the slower the current required to put it in motion.

The present tests show that the initial movement of terebratuloid brachiopods depends primarily on the effective density because that variable appears to govern whether a shell moves more easily than the sand on which it rests. Secondarily, the velocity required to initiate motion appears to depend on the shape and size of the shell. Although the movement of shells and of gravel and sand is necessarily controlled by the same physical characteristics, it is apparent that the relative importance of these characteristics varies.

EFFECTIVE DENSITY

All the whole *Terebratulina* shells tested were moved by currents which were incapable of moving the bed of sand, although the shells weighed as much as 0.605 gram and the sand grains weighed only a few thousandths of a gram. This seeming paradox is due to the very small density of the shell and its contained water as compared to the solid quartz grains. If shell number 4, for example, is filled with water, the shell-water combination has a density in air of 1.28 gms./cc.; however, if the combination is under water, the buoyancy of the displaced water reduces the effective density to 0.28 gm./cc. A water-filled shell moved by a slow current is analogous to an inflated balloon moved by the faintest breeze although the rubber in the balloon weighs several grams.

Species and individuals differ in effective density, and, therefore, in competent velocity. Hence moving water may tend to sort a mixture of individuals of two species into groups according to species—rather than size or shape—if the effective densities of the two species are very different and the range in size and shape is small. Some effective density determinations for terebratuloid brachiopods appear in table 1.[1] The values show that the effective density of *Terebratulina septentrionalis* ranges from 0.28 to 0.43 gm./cc., and that it decreases as the size increases. The effective density of *Terebratalia transversa* ranges from 0.35 to 0.42 but does not vary systematically with size.

Studies of sediment movement indicate that competent velocity is proportional to the square root of effective density. Applying this proportion to brachiopod shells suggests that the competent velocity of a one-centimeter *T. transversa* shell is only slightly larger than that of a *T. septentrionalis* shell of about the same size and shape.

SIZE

The size of irregularly shaped shells may be expressed in terms of a nominal diameter equal to that of a sphere of the

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[1] A dry shell was weighed in air, and the approximate volume was determined by dividing the weight by the density of calcite (2.72 gms./cc.). The shell was then filled with water and weighed. The weight of the dry shell was substracted from the weight of the water-filled shell in order to obtain the weight of the water, and thereby its volume. The density of the water-filled shell was calculated by dividing the sum of the volume of the shell and of the contained water by the total weight.

same volume. For the present purposes, a nominal diameter has been determined by taking the cube root of the product of the length, width, and thickness of each shell. Thirty-one shells (including single pedicle and brachial valves as well as whole shells) with nominal diameters ranging from 0.41 to 5.50 millimeters were moved while resting on a substratum of either medium-fine sand or gravel. The current velocity required to initiate the motion of each of the shells is shown in graphic form in figure 1, in which the competent velocity in centimeters per second is plotted against the nominal diameter in centimeters. The graph paper is logarithmic because experiments with sediments have shown that functions of these two variables yield a straight line on logarithmic paper. This relation provides an easy means of establishing whether or not the initial movement of shells is controlled by the size of the shells in the same way that the initial movement of sediment is controlled by the size of the grains.

The points relating competent velocity and nominal diameter in figure 1 are scattered, but the area in which the points lie has a trend which suggests that the velocity is proportional to the square root of the diameter, as it is for sand and gravel. The coefficient of correlation for a least squares regression line based on all the data in which the bed was sand gives a low positive correlation of 0.585.[2] If the data for a gravel bed are included, a high positive correlation of 0.820[2] is indicated. However, combining data from different experimental conditions introduces some bias into the calculations. The scattering of points indicates that the nominal diameter of a shell is not the only variable affecting its competent velocity. This indication agrees with the general body of hydrodynamical theory and observation. Rouse (1938, p. 216) says that if the wake behind an object is completely turbulent, the drag exerted upon the object by a moving fluid is almost completely independent of the Reynolds number (a criterion of turbulence). The Reynolds number in the present experiments is the product of the current velocity and the nominal diameter divided by the kinematic viscosity; the value of the Reynolds number is great enough to establish that the wake was always turbulent. With regard to shells (nominal diameter larger than about one centimeter), therefore, Rouse's statement indicates that

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[2] Computed by W. Peddle.

TABLE 1

Physical Characteristics and Flume Behavior of Terebratuloid Brachiopod Shells Resting on a Bed of Sand or Gravel

No.	Species	Type of Shell	Length (cm.)	Width (cm.)	Thickness (cm.)	Weight (gms.)	Sphericity	Nominal Diameter (cm.)	Effective Density (gm./cc.)	Medium Sand Bed			Gravel Bed
										Competent Velocity (cm./sec.)	Current Velocity At Which Specimens First Turned Over (cm./sec.)		Competent Velocity (cm./sec.)
											Single Valve Concave Upward or Whole Shell	Single Valve Convex Upward	
1	*Terebratulina septentrionalis*	Whole	2.41	1.99	1.21	0.790	0.745	1.80					
2		Whole	2.09	1.74	1.20	0.605							
3		Whole	1.82	1.40	0.81	0.365	.700	1.27		13.8	13.8		
4		Whole	1.70	1.36	0.82	0.325	.728	1.24	0.28	13.3	13.3		
5		Whole	1.63	1.17	0.74	0.230	.688	1.12	(0.30)	13.8	13.8		
6		Whole	1.32	1.10	0.65	0.165	.744	.98	0.32	15.1	15.1		
7		Whole	1.21	0.83	0.57	0.135	.687	.83	(0.36)	11.7	11.7		
8		Whole	0.98	0.75	0.44	0.085	.701	.69	0.43	15.1	15.1		
9		Whole	0.76	0.57	0.36	0.050	.708	.54		11.7	11.7		
10		Whole	0.62	0.46	0.38	0.035	.769	.48		11.7	11.7		
11		Whole	0.62	0.44	0.26	0.020	.667	.41		12.1	12.1		
12		Pedicle valve	2.29	1.60	0.69	0.407	.595	1.36		11.1	12.0	14.9	
13		Pedicle valve	1.92	1.49	0.51	0.307	.591	1.13		11.1			
14		Pedicle valve	1.81	1.34	0.48	0.225	.582	1.05		10.1	10.1	14.7	
15		Pedicle valve	1.61	1.11	0.43	0.115	.569	.92		10.1	10.1	14.9	
16		Pedicle valve	1.19	0.85	0.28	0.055	.551	.66		10.1	11.1 10.6	14.9	
17		Brachial valve	1.65	1.47	0.40	0.217	.600	.99		9.4		SMF*	
18		Brachial valve	1.57	1.31	0.51	0.257	.647	1.02		11.6	11.6	SMF*	
19		Brachial valve	1.50	1.35	0.34	0.135	.589	.88		9.4	10.6	SMF*	
20		Brachial valve	1.35	1.02	0.37	0.112	.592	.80		10.6	10.6	14.4	

TABLE 1 (*Continued*)

										Medium Sand Bed			Gravel Bed
											Current Velocity At Which Specimens First Turned Over (cm./sec.)		
No.	Species	Type of Shell	Length (cm.)	Width (cm.)	Thickness (cm.)	Weight (gms.)	Sphericity	Nominal Diameter (cm.)	Effective Density (gm./cc.)	Competent Velocity (cm./sec.)	Single Valve Concave Upward or Whole Shell	Single Valve Convex Upward	Competent Velocity (cm./sec.)
21	*Terebratulina septentrionalis*	Brachial valves	1.45	1.13	0.38	0.102	.590	.85		9.4	10.6	SMF*	
22			1.04	0.85	0.18	0.042	.522	.54		8.6	9.4	SMF*	
23	*Terebratalia transversa* (Sowerby)	Whole	1.41	1.61	0.68	0.255	.718	1.15	0.35	15.0	15.0	SMF*	
24		Whole	2.19	2.63	1.19	1.763	.721	1.90	0.42	SMF*			
25		Whole	2.74	3.22	1.46	3.036	.728	2.34	0.39	SMF*			SMF*
26		Whole	3.07	3.89	1.83	5.337	.719	2.80	0.41	SMF*			
27		Whole	4.00	4.28	2.53	10.384	.820	3.52	0.37	SMF*			
28		Whole	3.55	4.53	2.30	9.400	.745	3.38		SMF*			SMF*
29	*Magellania flavescens*	Whole	2.95	2.35	1.63	2.496	.761	2.24		17.6	17.6		
30	*Terebratalia rubescens*	Whole	1.94	2.72	1.15	1.467	.639	1.82		SMF*			
31	*Neothyris venosa* (Solander)	Whole	6.95	6.33	3.78	18.677	.791	5.50		SMF*			26.8
32	*Laqueus californicus*	Pedicle valve	3.55	3.90	1.15	5.445	.694	2.52		SMF*			
33		Brachial valve	3.60	4.22	1.15	2.65	.679	2.60		17.6	17.6		
34	*Terebratulina caput-serpentis* (Linné)	Whole	1.96	1.65	0.86	0.410	.718	1.41		17.6			
35	*Waldheimia florida* (Portales)	Pedicle valve	2.05	2.23	0.94	0.295	.650	1.63		12.6			
36		Brachial valve	1.75	2.23	0.59	0.214	.528	1.32		14.8	14.8	16.7	
37		Whole	2.17	2.28	1.50	0.703	.770	1.95		12.6	12.6		
38	*Laqueus californicus*	Whole	2.79	2.44	1.45	0.675	.770	2.14		12.6	12.6		
39	*Terebratella dorsata* (Gmelin)	Whole	3.48	3.63	2.08	4.751	.859	2.98		SMF*			26.8

* Sand Moved First.

( ) Parentheses indicate interpolated values.

the current velocity necessary to initiate motion may even be independent of the size.

SHAPE

The shape of shells may be expressed in terms of *true sphericity*—the surface area of a sphere divided by the surface area of a shell of the same volume (Wadell, 1932). Because the surface area of a shell is difficult to measure, the shape is here expressed in terms of ratios of diameters—the *intercept sphericity* of Krumbein (1941). Intercept sphericity is equal to the cube root of the following quantity: the intermediate diameter times the smallest diameter divided by the square of the largest diameter. This is an approximation of sphericity as defined by Wadell. In the present tests, the thickness is always the small diameter, but either the width or length may be the intermediate or large diameter. Sphericity for the 31 shells which were moved had a range of 0.522 to 0.859.

It will be shown in the following paragraphs that there is a correlation between the intercept sphericity of a shell and the

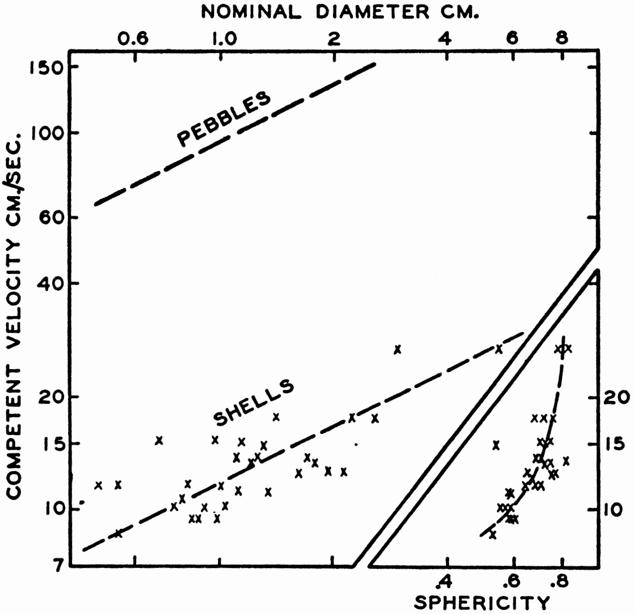

Fig. 1. Competent velocity of terebratuloid brachiopod shells in relation to nominal diameter and sphericity. The competent velocity of pebbles is shown for comparison.

current velocity required to put it in motion. The correlation appears to indicate that intercept sphericity is an index of the shape of terebratuloid brachiopod shells; but the correlation does not mean that the intercept sphericity represents a complete expression of the shape of the shells. Intercept sphericity represents an approximation of true sphericity which holds because of the general resemblance between pebbles and a triaxial ellipsoid. If the intercept sphericity is a valid expression for the shape of only those shells which resemble triaxial ellipsoids, it will prove of little value in measuring the shape of most shells which, unlike terebratuloid brachiopods, are irregular. It is interesting to note, however, that in the present experiments with single valves the intercept sphericity appears to give a more accurate expression of shell shape than does the true sphericity. True sphericity appears to have little significance as a measure of the shape of single valves because each valve is essentially a curved plate, and this sphericity takes no account of the curvature of such a plate.

Engineers divide the total drag exerted on an object by a moving fluid into two parts: "surface drag" resulting from the retardation of the fluid at the solid boundary, and "form drag" resulting in large part from the pull exerted by the low pressure area in the wake of the particle. Neither true sphericity nor intercept sphericity is an exact expression for the sum of surface and form drag; hence neither is capable of measuring the total effect of shape upon the hydraulic behavior of a particle. True sphericity appears to be an index of surface drag but it takes little account of form drag. Consequently it gives an indication of the hydraulic behavior of particles of approximately the same shape, but not of particles with very different shapes, because the wakes are different. Intercept sphericity gives some measure of the surface drag of ellipsoidal particles and also of form drag, because it is based on ratios of diameters. With regard to hydraulic behavior, therefore, intercept sphericity may surpass true sphericity as an index of shape of sand and gravel particles. Irregular shapes such as shells are far more complex, and their hydraulic behavior will not be understood completely until the principles of fluid dynamics are applied to their study. Neither true nor intercept sphericity, for example, is capable of indicating any significant difference in the hydraulic behavior of a rectangle and of an airfoil of about the same dimensions, although the form drag of the airfoil is much less than that of the rectangle, and the lift resulting from the shape of the airfoil might have a pronounced effect on its movement. A section of a pecten perpendicular to the hinge line resembles an airfoil, so it is doubtful if any type of sphericity would provide a significant index of its shape in relation to hydraulic behavior.

Figure 2 shows the sphericity of the various shells graphed against the current velocity required to put them in motion. For purposes of comparison, the figure also shows the effect of particle sphericity on the settling velocity and competent velocity of synthetic pebbles with a nominal diameter of about 14.5 mm. (Krumbein, 1942), and also on the settling velocity of molded lead particles (Wadell, 1934). The points relating sphericity and competent velocity of shells are scattered, and the trend of the relation is subject to several interpretations. The four most reasonable interpretations are shown in figure 3. In the first and second interpretations, the data for single valves and whole shells are combined; therefore the relation between sphericity and competent velocity is assumed to be continuous as shown by Wadell (1934). In the third and fourth interpretations, the data for single valves and whole shells are separated; therefore it is assumed that the relation is discontinuous (but continuous for various classes of shapes, such as rollers, disks, or spheriods) as shown by Krumbein (1942). In the first and third interpretations, the data for movement on a sand bed are combined with the data for movement on a gravel bed; in the second and fourth interpretations, these data are not combined. Statistically there is reason to separate the data concerning movement on two sizes of bed material because the experimental conditions were different; combining the data may bias any interpretation. Hydraulically the bias does not appear to be important. The change in bed type probably altered the boundary conditions of the flow in the flume; this probably altered the distribution of velocity in the main body of the flow but the average alteration probably was minor. The shells were all large compared to the thickness of any laminar boundary layer, and therefore most of the surface of shells on either the sand or gravel bed was exposed to the relatively undisturbed turbulent flow outside the boundary layer. The data are subject to too many interpretations to justify any more extensive discussion of this bias.

Despite their diversity, the interpretations indicate that there is some correlation between the sphericity of a shell and the current velocity required to move it. Some measure of the correlation can be determined by drawing a least square regression line for each interpretation, and calculating a coefficient of correlation for the deviation of the points from that line. Interpretation one (figure 3) gives a positive correlation of 0.699[3] for the straight line; no coefficient of correlation can be calculated for a curved line. "Positive" applied to a correlation

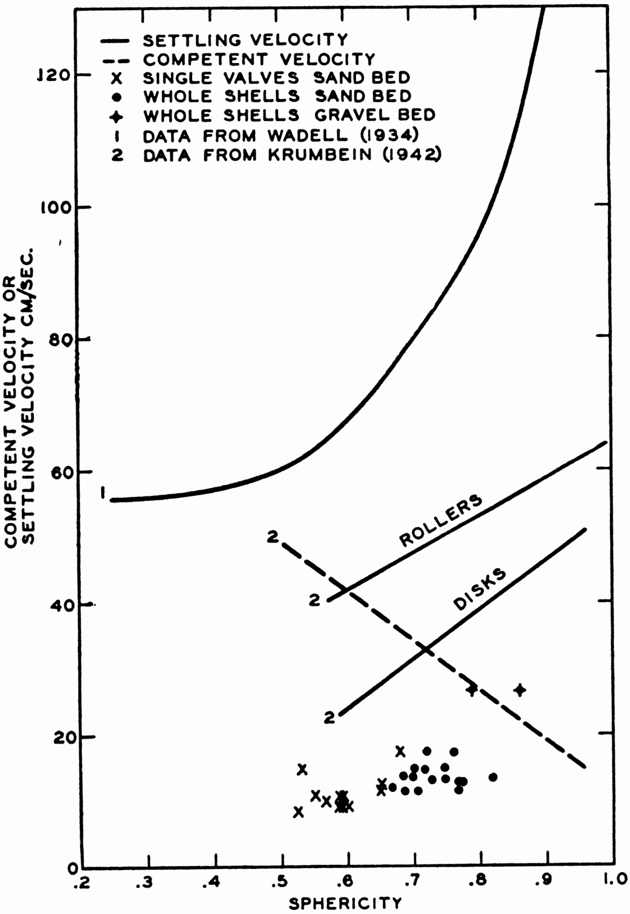

Fig. 2. Effect of sphericity upon the competent velocity and settling velocity of various kinds of particles.

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[3] Computed by W. Peddle.

coefficient refers only to its algebraic sign. It is not an indication of certainty. Interpretation two gives a low positive correlation of 0.603 for whole shells.[4] Interpretation three gives a low positive correlation of 0.588. Interpretation four gives a positive correlation coefficient of 0.069 for whole shells, indicating no correlation; for all single valves together it gives a low positive correlation of 0.495; for single valves of one species, *Terebratulina septentrionalis*, it gives a positive correlation of 0.659. Thus almost all of the interpretations suggest that the competent velocity of a terebratuloid brachiopod shell depends on the sphericity of the shell; but part of the fourth interpretation indicates no such dependence for the limited number (16) of observations of the movement of whole shells included in the interpretation.

Sphericity is related to shape insofar as the hydraulic behavior of these shells is concerned, but the relation is only approximate. Hence two shells with the same weight, size and sphericity may have different competent velocities because of the shape effect which is not included in the sphericity. This unmeasured shape effect may account for some of the scattering of points in the graphs relating sphericity and competent velocity. Scattering may also be due to the action of turbulent eddies which cause the instantaneous velocity around a shell to vary from the mean velocity.

The present tests with terebratuloid brachiopod shells resting on a substratum of sand indicate that the more spherical shells require a faster current to put them in motion. This qualitative relation between sphericity and competent velocity is diametrically opposed to a relation observed by Krumbein (1942). Krumbein molded a number of artificial pebbles which had about the same weight and nominal diameter but different sphericities. He placed these pebbles in a flume and then observed the velocity required to initiate motion as well as the relative velocity of the current and the pebbles once they began to move. The competent velocities were not published; however, in a letter to Menard in 1949, Dr. Krumbein was kind enough to state that the competent velocity for spheres averaged 14.5 cm./sec., and that for pebbles with a sphericity of about 0.5 the competent velocity averaged 42.2 cm./sec. Thus the velocity required to initiate motion appeared to vary inversely

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[4] Computed by W. Peddle.

with the sphericity. Computations by the present writers using Krumbein's published data on critical Froude numbers yield the competence-sphericity relation shown in figure 2.

On the other hand, Krumbein (1942) also measured the settling velocity of the artificial pebbles, and his figure 4 (p. 627) shows that the settling velocity varies directly with the sphericity. Wadell (1934) had noted a similar relation between settling velocity and sphericity. Both Krumbein's and Wadell's data are plotted in figure 2. The settling velocity of particles larger than a few millimeters in diameter is directly proportional to the competent velocity (Hjulstrom, 1935; Menard, 1949). Consequently, with regard to the relation between competent velocity and sphericity, Krumbein's tests with settling velocities agree with the flume tests of the present writers.

The contradictions in observations of the competence-sphericity relation of particles in flumes may be more apparent than real. A particle is put in motion in a flume if the propelling

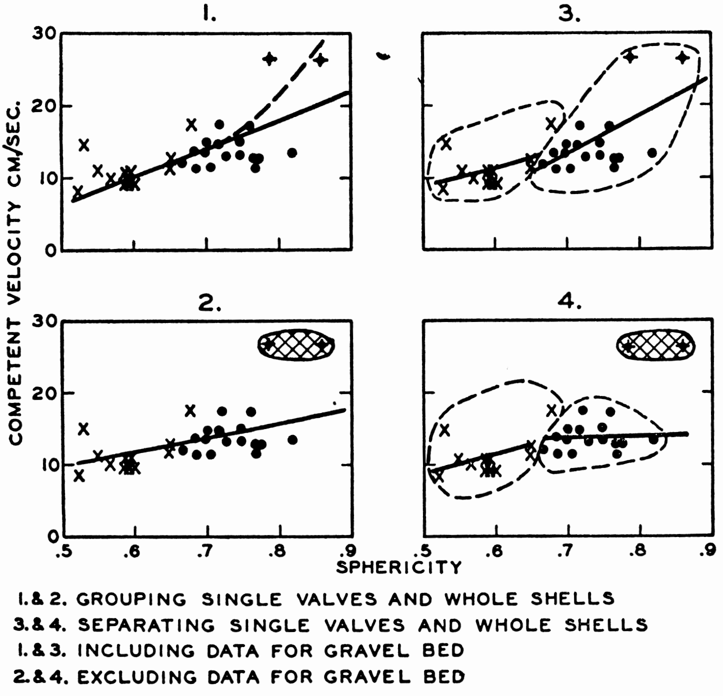

Fig. 3. Possible interpretations of the effect of sphericity upon the competent velocity of terebratuloid brachiopod shells.

force due to moving water exceeds the retarding force due to friction between the particle and the adjacent particles of the bed. Particle shape may have some influence on the effectiveness of both the propelling and the retarding forces. Tentatively, the present writers believe that the differences in the observed influence of sphericity on competence may be ascribed to the differences in the effective density of the particles in the two experiments. The effective density of the shells is less than one-fifth of the effective density of Krumbein's synthetic pebbles. The shape of the shells may have more influence on the effectiveness of the drag due to the moving water than on the effectiveness of the friction between the shells and the sand bed. As a result the relation between sphericity and competence of shells in a flume corresponds to the relation between sphericity and settling velocity (in which there is no friction with adjacent particles). With denser particles, however, the proportion of the grain surface exposed to moving water is much smaller compared to the surface in contact with other particles. Therefore, the influence of particle shape on the effectiveness of the retarding force due to friction between grains may be more pronounced than the influence on the effectiveness of the propelling force due to moving water. If so, the relation between sphericity and competence of solid particles in flumes would depend on the relation between sphericity and friction between grains, and could be just the opposite of the relation between sphericity and the settling velocity of the particles. Granting the validity of both sets of apparently contradictory observations, the fluid velocity required to move shells probably varies directly with the sphericity, but the fluid velocity required to move most solid detritus (density about 2.7 grams per cc.) probably varies inversely with the sphericity.

Although the conclusion is speculative, some field observations also suggest that the velocity required to move shells varies directly with the sphericity. DuBois (1916) found that individuals of *Terebratalia obsoleta* (Sowerby) taken from Puget Sound varied in shape according to the degree of movement of the waters in which they lived. The more spherical shells were developed in the fastest currents. As the variation in shape represents an adaptation to differences in current velocity, the more spherical forms must be those which are best adapted to live where the currents are faster. The shape may be related to some secondary characteristic of fast currents—such as an increased oxygen or food supply—but if the adaptation of shape is necessary in order to counterbalance the velocity of the water, a more spherical shape must be the one which is least affected by moving water. Therefore, the velocity necessary to initiate motion appears to vary directly with the sphericity.

ORNAMENTATION

The effect of variations in ornamentation upon the movement of shells can not be evaluated from the present tests because all the shells are relatively smooth. Variations in ornamentation, however, are variations in shape, so it is apparent that they influence the relative ease with which a shell may be put in motion.

HYDRAULIC FACTORS

The initial movement of a shell on the sandy bed of a watercourse is influenced not only by the characteristics of the sand and shell but also by the flow characteristics of the running water. Friction retards the layer of water next to the bottom and sides of the channel so that the velocity of the water on a sand bed may be only a fraction of the mean velocity of the current. However, the retarded or "boundary" layer rarely is more than a millimeter thick; all but the smallest shells protrude through it and are exposed to the force of the current. Medium and fine sand grains, however, usually lie within the boundary layer and thus may remain undisturbed on a stream bed although shells which are larger and heavier are in motion.

The measured effective densities of terebratuloid brachiopods are so small that the initial motion of any particular shell probably is influenced by the degree of turbulence of the moving water. Hjulstrom (1935) has shown that all natural watercourses are characterized by turbulent, eddying motion. The eddies may move in any direction relative to the general motion of the water, with the result that at any instant some parcels of water move faster than the average and some move slower. Due to the entirely random motion in a turbulent fluid, a comparatively rapidly moving eddy may strike a large shell and put it in motion although a smaller shell only a few centimeters away remains fixed in position because the force of the water in that place is much smaller. The analogous effect of turbulence in air may be observed when a gust of wind swirls a patch of dust upward while the surrounding dust remains in place, or when a "cats-paw" ripples a water surface in some spots but leaves the remainder smooth. These commonplace phenomena indicate how turbulence may cause the larger of two shells of the same species to be moved instead of the smaller.

The quantitative importance of the turbulent eddies with regard to initiating motion in whole shells depends on the comparative velocity of the eddies and the current as a whole. This relation has been the subject of a great deal of study by hydraulic engineers, and it is known that the importance of the eddies increases with the cross-sectional area of the current if all other things are equal. In a small stream, for example, the eddy velocity might be only a fraction of the current velocity, but in a large slow current on a continental shelf the eddies might flow several times as fast as the average current velocity.

Perhaps the most significant conclusion to be derived from this analysis is that some terebratuloid brachiopod shells may be moved so readily that they are capable of being transported by the low current velocities now found on the continental shelves and slopes. All sizes of *Terebratulina septentrionalis* tested were moved by currents with velocities of 11.7 to 15.1 cm./sec.; Shepard (1948) has recorded bottom velocities of 36.7 cm./sec. in 160 fathoms on the California continental borderland, and 14.6 cm./sec. in 1050 fathoms in the Santa Cruz basin. These velocities were measured in the open ocean where tidal effects were negligible. However, in bays and estuaries where the tidal range is large, current velocities commonly are several times as great.

WHOLE SHELLS WHICH ARE MORE DIFFICULT TO MOVE THAN THE UNDERLYING SAND

Flume tests with individuals of *Terebratalia transversa* show that the transportation of shells may depend on a critical relation between the competent velocity of the shells and of the sand in the bed. The smallest of five individuals resting on a bed of monodisperse sand grains with a median diameter of 0.36 mm., was moved by a velocity of 15.0 cm./sec. At the same time the sand was scoured from around the remaining four larger shells. A faster current caused the whole surface of the bed to move although the shells remained fixed. They then began to settle into holes in the sand which were produced by the scour around them. This sequence of events is depicted in figure 4. Similar scour around pebbles was noted in earlier experiments in the flume, and fossil scour marks have been observed by Peabody (1947) in the Moencopi formation of the Grand Canyon area. If a current moves the subjacent sand instead of a shell the shell may become buried. However, this burial may depend on whether the sand is being eroded or

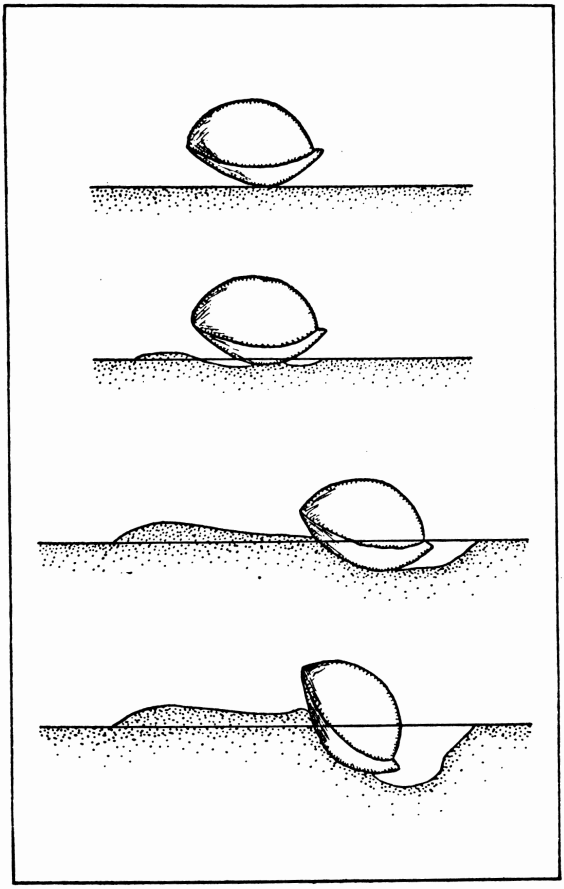

Fig. 4. A terebratuloid brachiopod (*Terebratulina septentrionalis*) being buried in sand because of scour by moving water. Four stages in the burial, of which the first is uppermost, are depicted in cross sections parallel to the direction of flow. In all the stages the water is moving from right to left, and at a constant velocity.

deposited; if erosion prevails, the shell remains exposed, whereas if deposition prevails, it is covered.

It follows that the size of the grains in the bed may determine whether a shell is moved by water with a given current velocity. A current which could move a shell on a bed of coarse sand might cause it to be buried in a finer sand, because the latter would be scoured from around the shell.

The effect of the size of particles in a substratum is shown by the tests with shells number 31 and 39. If these shells were resting on medium sand, they began to be buried when the current velocity was less than 20 cm./sec. and they did not move even when the velocity was increased to the maximum that the flume could produce—about 35 cm./sec. On the other hand, both shells were put in motion by a current with a velocity of 26.8 cm./sec. if they were resting on a substratum of gravel.

In order to establish whether an assemblage of fossil shells can have been transported over a bed of the sand in which it is enclosed, it is necessary to know the competent velocity required to move both the sand and the shells. The competent velocity for any size of sand is known within certain limits (Hjulstrom, 1935), but the velocity required to move any particular shell can be found only by the type of experiment reported in this paper.

SINGLE VALVES

Five pedicle valves of *Terebratulina septentrionalis*, weighing 0.055 to 0.407 gm. and oriented concave upward, were tested simultaneously. All were moved small distances by a current with a velocity of only 11.1 cm./sec. In other tests these shells were oriented convex upward, in which position one valve weighing 0.115 gm. was moved by a current of 11.1 cm./sec., and the other valves were moved small distances by a current with a velocity of 14.9 cm./sec.

Another series of tests featured the six brachial valves of the same species. These valves weighed 0.042 to 0.257 gms. Their behavior at several current velocities is shown in table 2. If the current velocity was increased to more than 14.4 cm./sec. the sand bed began to move and ripples were formed. The valves (convex upward) continued to be fixed in position until a sand ripple moved past. Each then was turned over and moved into the trough behind the ripple; it remained in the trough as the ripple slowly moved downstream.

MOVEMENT OF SHELLS

Most of the whole hinged shells moved over the sand bed by rolling with their longest dimension perpendicular to the current; however, others slid or rolled end over end. At higher current velocities almost all of these latter shells would probably roll with their longest dimension perpendicular to the current, because this position affords the least resistance to movement. Most of the sliding shells maintained a constant orientation relative to the current, but the individuals usually had different orientations. Both sliding and rolling were episodic; a shell slid a few centimeters in a few seconds, then remained fixed for several minutes, and slid or rolled again. The episodic nature of the movement may have been due to the intermittent action of eddies which locally increased the mean velocity enough to initiate movement, but soon dissipated and no longer moved the shell.

The *Terebratulina* shells moving over an immobile sand bed came to rest at random orientations relative to the direction in which the current was moving. In a fossil state these shells would give no clue to the direction of the water movement at

TABLE 2

Movement of Brachial Valves of *Terebratulina septentrionalis*
(Initial Orientation Concave Upward)

No.	Weight (gms.)	Behavior At Current Velocity (cm./sec.)				
		8.6	9.4	10.6	11.6	14.4
18	0.257				Turned over	
17	0.217		Slid 2 cm.	Turned over		
19	0.135		Slid 10 cm.	Turned over		
20	0.112			Turned over		Rolled and slid 2 cm.
21	0.102	Twisted 5°	Slid 20 cm.	Rolled 20 cm. end over end, concave upward	Moved out of flume	Moved out of flume
22	0.042	Slid several cm.	Slid 10 cm. and turned over	Slid 30 cm.	Moved out of flume	Moved out of flume

the time they were deposited. What is more significant to paleoecology is that a small number of shells may have a chance parallel orientation, but that there may be any relation between the shell orientation and the current direction.

Single brachiopod valves moved both by sliding and by turning over so that they were alternately convex upward and downward. It was noticed that the single valves which became buried always did so in a convex-upward attitude, this position seemingly being most stable in the flume. According to the evidence of these tests, however, there is no reason to believe that orientation in sedimentary rocks can be demonstrated by the direction of convexity of a small number of valves, because a sudden stilling of the flow in the flume would have found some valves convex upward and others downward. The sequence of sedimentary rocks may be strongly suggested by consistent orientation of the direction of convexity of a considerable group of brachiopod valves (Shrock, 1948), but the possibility of error increases as the number of valves diminishes.

SUMMARY

1. Some terebratuloid brachiopods are moved by currents in a flume which are moving no faster than natural currents found at a depth of more than 1000 fathoms in the Pacific Ocean.
2. The very low effective density of a shell and its enclosed water permit it to be moved by running water even though it weighs hundreds of times as much as any one of the motionless grains of sand over which it is rolled.
3. The velocity required to initiate the motion of a shell depends on the sphericity (shape) of the shell as well as on the size and weight. The smaller the effective density, the more important the shape.
4. Shells which are more difficult to move than the subjacent sand settle into scours which are formed in the sand around them.
5. The movement of a shell is a function of both current velocity and size of the subjacent sand grains. The same current moves a shell on one stream bed but not on another, depending upon the sand size.
6. The orientation of a small number of movable shells is essentially random in relation to current direction.

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