Experimental and theoretical hydrodynamic analysis of *Mercenaria* valves from the Florida Pinecrest beds

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ABSTRACT

Upper Pliocene Pinecrest beds exposed in west-central Sarasota County, Florida, display distinct basal lags, dominated by *Mercenaria mercenaria* valves (≤14 cm length, estimated pre-diagenesis mass ≤ 400 g). The valves are some of the largest sedimentary particles in nearly all Plio-Pleistocene shell beds in Florida. They are typically disarticulated and unbroken, and are found in situ with varying orientations, including hydrodynamically unstable concave-up positions, indicating movement and rapid burial.

To constrain the transport conditions for these valves, empirical hydrodynamic analyses were done of modern *Mercenaria* using a flume 15.2 m long x 61 cm wide, where entrainment velocities were determined through incremental increase in flow velocity to the point of movement. Entrainment conditions were varied for shell orientation, by turning the umbo of the shell directly into or away from the direction of flow. The velocity of flow required for entrainment was recorded using 2-dimensional Acoustic Doppler Velocimetry (ADV), and the associated critical shear stress was estimated using 3-dimensional ADV in velocity profiles. Steady-state flume tests were conducted using Particle Image Velocimetry (PIV) technique, to examine the characteristics of flow around a *Mercenaria* valve in different orientations, and at different velocities and Reynolds numbers.

Velocity of entrainment was found for five modern shells to be between 67.8 and 82.9 cm/s with their umboes into the direction of flow, with a strong positive correlation between mass of the shells and the entrainment velocity ($r = 0.99$). Critical bed shear stress ranged between 0.13 and 3.58 kg/ms². With umboes facing directly away from the direction of flow, the flume was unable to entrain any of the valves, with maximum flow velocities over 150 cm/s. Flow visualization showed centimetric areas of flow separation over the valves facing in both directions, and indicated similarities to the properties of airfoils for those with umboes facing forward.
INTRODUCTION

Study Area and Sedimentological Background

The area of interest for this project is SMR Aggregates quarry (SMR, formerly Quality Aggregates), approximately 30km NW of Sarasota, near the western coast of Florida. The Pinecrest sands exposed at this location contain the oldest and most species-rich beds of Plio-Pleistocene Florida, containing as many as 1200 species of mollusks (Olsson, 1968). These beds have been the subjects of numerous taxonomic studies and paleoenvironment reconstructions (Jones, 1991; Allmon, 1993; Jones, 1995; Daley, 2002), but there is less taphonomic research contributing to the understanding of the conditions of formation (Meeder, 1987a; Meeder, 1987b; Geary and Allmon, 1990; Allmon, 1991; Allmon et al., 1995). Winnowing has been considered as a possible cause of the high fossil concentrations and preferential removal of fine sediments. Nocita and Allmon (1991) found that mud content is normally less than 5% by mass. Among those mollusks contained in the beds at SMR, Mercenaria mercenaria is the largest and heaviest species found, usually over 10 cm in length, and with masses between 100 and 400 g. Unlike similar outcrops towards the eastern coast of the peninsula (Dickerson Pit, Ruck’s Pit) where unbroken, disarticulated Mercenaria are almost always found in situ with convex-up orientations, those specimens at SMR are found in various positions—including many hydrodynamically unstable concave-up examples. The presence of these shells and the atypical in situ orientation has led to interest in the necessary flow conditions for entrainment of Mercenaria.

Several studies have attempted to examine the behavior of disarticulated bivalves and brachiopods as they settle through water or are entrained by unidirectional flow
Figure 1: Map of Florida with shelly sediment areas. Primary fieldwork was done at SMR Aggregates Quarry near the western coast of the Florida peninsula, and at Dickerson Pit, approximately 65 km to the southeast. Both locations featured large disarticulated fossil *Mercenaria mercenaria* valves, although those at SMR Aggregates were found buried in concave-up orientations, while *Mercenaria* in situ at Dickerson Pit were almost always concave-down.
Figure 2. Exposure of Pinecrest shelly sands at SMR Aggregates in Sarasota, FL. Close-up photographs show basal lag with high concentration of large, disarticulated *Mercenaria mercenaria* valves (denoted by arrows). Many of these fossils were found buried in unstable concave-up positions, in contrast to other Pliocene shelly sediments of the region, where large bivalve fossils are usually concave-down.
(Allen 1984; Olivera, 1995; Olivera and Wood 1997; Thompson and Amos, 2002; Messina, 2004). Allen (1984) describes the entrainment or overturning of a valve as controlled by a non-dimensional ratio proportionate to the applied fluid force on the particle and the immersed weight of the particle. This result is supportive of the hypothesis that the heavy bivalves will resist entrainment, if the fluid force applied to them is similar to that of lighter shells. The most complete discussion on the topic is provided by Olivera and Wood (1997), who measured the influence of specific features of bivalve morphology on the applied fluid force described by Allen (1984).

**Hydrodynamic Background**

The comprehensive work done by Olivera and Wood (1997) uses flume and flow visualization experiments, as well as pressure-sensing models, to show that bivalves varying in size, shape and surficial texture experience different forces applied by unidirectional flow. In general, it was observed that disarticulated shells of most bivalve types have a cross section similar in shape to an airfoil when oriented with their umboes facing the direction of flow. Consequentially the flow over a valve oriented this way experiences pressure drag and lift forces due to steep pressure gradients, much like those produced by an airfoil in moving air. However, because the 3-dimensional shape of a disarticulated valve may vary greatly between species, a number of morphological parameters have an effect on the amount of lift and drag experienced by a valve in unidirectionally flowing water. Those characteristics found to be influential by Olivera and Wood (1997) include:
• **Roughness/Ornamentation:** Effects of roughness are much like those for spheres, although it is noted that turbulent transitions occur at lower Reynolds number for shells than for spherical bodies. Thin growth lines, like those found on *Mercenaria*, have little effect on drag. Shells with large and profuse ornamentation tend to exhibit less drag than similar specimens with less pronounced ornamentation.

• **Surface Area/Concavity:** Increase on plan area and concavity (width/length), and the associated frontal area, leads to an increase in lift and drag forces. Thus, shells of similar masses will often entrain at lower velocities for larger specimens because of the greater forces generated by their shape.

• **Elongation:** Valves elongated in the direction parallel to flow (those with higher height/length) tend to create larger destabilizing lift and drag forces than shorter valves of otherwise similar morphology.

• **Asymmetry:** Asymmetric morphology leads to unstable asymmetric pressure fields, aiding in entrainment as well.

In the aforementioned flow visualization experiments, Olivera and Wood (1997) noticed flow separation over the high point of almost all umbo-forward valves, and reattachment at the far edge. The point of separation jumps downstream slightly with flows of high Reynolds number (\( \text{Re} = \frac{\rho LV}{\mu} \), L is a characteristic length, V is flow velocity and \( \mu \) is the dynamic viscosity), usually transitioning at \( \text{Re} \sim 4 \times 10^5 \). Shown in pressure maps of several tested valves, there is typically a steep positive pressure gradient over the frontal slope of the valve, and a rapid drop in pressure into the negative range in the area of flow separation. Pressure on a valve increases again with downstream reattachment. These gradients are the source of lift and pressure drag experienced by the
valve body. Olivera and Wood (1997) also note that vortices and areas of separation increase in size with larger concavity, although these vortices tend to be less visible in high velocity/high Re flow conditions.

To create a simplified model the velocity necessary to entrain a valve, Olivera and Wood (1997) cancel the frictional force holding the valve in place with the opposing drag forces, simplifying the entrainment as the equality of immersed weight ($W_I$) with the lifting force ($F_L$). As adapted from other fluid dynamic research (Olivera 1995), lift on the valve body can be expressed as

$$F_L = C_L \left( \frac{1}{2} \rho V^2 A \right)$$

(1)

where $A$ is the projected plan area of the body and $\rho$ is fluid density. $C_L$ in this equation is the coefficient of lift, an experimentally derived parameter that accounts for morphological features of the body and the Re of flow. By setting $W_I$ equal to the right side of the expression, solving for $V$ yields

$$V = \left[ \frac{2W_I}{C_L \rho A} \right]$$

(2)

thus providing a means to predict entrainment velocity by lift, with the estimation of $C_L$ for the tested shell type. Olivera and Wood (1997) also note that entrainment of a valve by overturning happens about a pivot at the farthest downstream point of contact with the bed, such that the upstream edge of the valve first lifts off of the substrate, rotating around the pivot.

The 11 species tested by Olivera and Wood (1997) were entrained on a loose sand substrate, and then a fixed-grained surface to prevent the effects of bedforms. Successful entrainment was recorded at the first initiation of movement.
Figure 3. Schematic diagram of a typical *Mercenaria mercenaria* valve in projected plan view (A), and frontal view (B). Valve is SMR-8-5A 1 of 4 #2L, collected from Pinecrest sediments at SMR Aggregates Quarry in Sarasota County, FL. Arrow shown in A indicates the direction of flow in umbo-forward experiments.
**Mercenaria as a Body in Unidirectional Flow**

Disarticulated valves of *Mercenaria mercenaria*, present an airfoil-like cross-section when the umbo is facing into the direction of flow. They exhibit large frontal and projected plan areas relative to other bivalve types, resulting from the dimensions of the shells. At approximately 130 cm², the largest *Mercenaria* nearly doubled the projected plan area of their largest Olivera and Wood (1997) counterparts, and similarly exceeded them in frontal area. The valves have modest elongation, between 0.81 and 0.87 for all fossil valves collected at SMR, and all modern valves used in flume experiments. The valves have moderate concavity as well, with thickness indices (thickness/height) of between 0.29 and 0.36. Ornamentation on the surface of *Mercenaria* is limited to fine growth lines running latitudinally over the shell surface, unlikely to produce substantial alteration to lift and drag. The umbo of *Mercenaria* is gradually rounded, presenting an overhanging region to flow, possibly a source of lift. Although the umbo does curve away to one side, *Mercenaria* tend to be relatively symmetrical when viewed in plan or from the direction of flow in either an umbo-forward or umbo-away position.

**METHODS**

**Approach**

Because valves from SMR were frequently found in concave-up positions, we define entrainment for our experiments as the overturning of a valve in unidirectional flow, not as the first movement of the valve. Entrainment of this type requires two
parameters: sufficient flow velocity for transport, and a high enough frictional force between the valve and substrate to prevent sliding as the primary means of transportation. Because of the second constraint, we designed the entrainment experiments to prevent the valves from sliding along the floor of the flume, so that overturning was the only means of entrainment.

**Experimental Procedure**

**Flume Tests:**

Entrainment experiments were done using a custom-built glass-walled flume at the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota. Valves used in these experiments were modern specimens collected in south Florida, chosen to represent a range of sizes containing and exceeding those of the largest specimens found in situ at SMR Aggregates Quarry on the western coast of the Florida peninsula, and the Dickerson Pit quarry towards the eastern coast. Although fossil shells were available for both locations, modern specimens were used in their place because of the deterioration of many fossils, leading to lower density, damaged ornamentation and a greater risk of breakage. The flume was 24” (~61 cm) in width, and approximately 15.2 m in length. For these experiments, honeycomb flow-straightening baffles were used to smooth turbulence at the head of the flume. Depth was controlled using adjustable-height obstructions spanning the tail of the flume. Each experiment was conducted by gradually increasing flow velocity until the valve was dislodged and tumbled over the top of the sheet. The control system was hydraulically actuated disk-valve, directly above the head tank of the flume. Because of the non-linear velocity response of the controls, entrainment velocity
was often fine-tuned once rough estimates of the necessary velocity were established. A flat-lying retaining sheet, 1 mm high was placed across the flume bottom to prevent the valve from sliding. The sheet was chosen to retain the tested valve because it provided a consistent force in resistance to sliding, and also produced little observable alteration to flow. Because the overturning of a valve happens about a pivot point at the downstream edge of the valve, friction after the initial lifting is provided only through a very small point of contact. The retaining sheet preserves this behavior in entrainment by overturning. The valves were placed into stable flow conditions and turned within the stream to release trapped air from the concave side. They were then placed flush against the lip of the steel sheet, at the center of the flume. Valves were oriented such that the sheet ran tangent to the valve lip, and orthogonal to the axis of symmetry running from dorsal to ventral edge. The valves were held in place with a thin aluminum rod, chosen to minimize interfering turbulent effects for a clean initiation of the trial. A non-entrainment test was confirmed after a valve remained in stable flow for two minutes without dislodging of the valve from its initial position.

Velocity was recorded using a Sontek FlowTracker Handheld 2-Dimensional Acoustic Doppler Velocimeter (ADV). Measurements were taken immediately following successful entrainment, in the center of the flume approximately 0.5 m downstream of the shell location (to avoid interference) and at approximately 4 cm above the flume bottom. Recorded velocity was time-averaged over a minute at a rate of one reading per second.

As velocities approached that required to entrain a valve, behavior of the valve was predictable. The specimen would often reorient slightly in flow before staying in place for all or part of the two-minute experiment. At an average velocity within a few cm/s of
that of entrainment, valves typically move or are entrained after remaining motionless in flow for up to a minute. The likely cause of this behavior is instantaneous variation in flow velocity. This variation was shown in greater detail with higher resolution tests done with 3-Dimensional ADV, showing rapid fluctuation of velocity of sometimes over 10 cm/s above or below the mean for an experiment. Experiments with the umbo of the valve facing away from the direction of flow were also performed, using an identical technique.

**Velocity Profiles:**

To describe entrainment in terms of critical shear stress, velocity profiles were constructed at the velocities of entrainment for each of the modern valves used in entrainment experiment. The flume was set to the average velocity of entrainment at the height of the shell (~4 cm above the bed), and then measurements were taken with a Sontek 16-MHz MicroADV, starting at approximately 3.5 cm above the bed, then moving directly upward by 1.5 cm intervals until the ADV was too close to the surface of the water to give reliable readings.

**Flow Visualization:**

Flow visualization experiments were conducted to qualitatively analyze the characteristics of flow over *Mercenaria* valves. These tests were conducted using a smaller custom flume at SAFL (12.2x0.15x0.4m). This equipment included recirculation capacity. The bottom material was smooth tile, providing enough friction to keep the
valves in place at mean velocities up to 50 cm/s (measured ~4cm above flume bottom, center of flume). Velocity in the flume was measured using a Sontek 16-MHz MicroADV. Valve NDM-1 was placed in the direction of the flow, first with the umbo forward. A sheet laser was placed above the shell such that the beam illuminated a line of symmetry parallel to the direction of flow. With the flume operating at a steady velocity, rhodamine B dye was injected at the floor of the flume, approximately 40 cm ahead of the tested valve, to illuminate turbulent effects around the shell body. The process was then repeated for the same valve in an orientation with the umbo away from the direction of flow. Experiments were done for the valve initially at a mean shell-level flow velocity of approximately 10 cm/s. Following runs with both orientations, the experiment was repeated at two higher velocities, with means of approximately 30 cm/s and 50 cm/s respectively. This approached the upper limit of velocity for the experimental setup, as sliding was initiated for the umbo-forward orientation at only slightly faster velocities. In all cases, Reynolds number was calculated to be between $1 \times 10^4$ and $1 \times 10^5$, with depth ranging from 10-11 cm.

**RESULTS**

The flume test entrainment velocities determined for modern shells ranged from 67.8 cm/s for the lightest modern valve and 82.9 cm/s for the heaviest modern valve. There is a strong positive correlation between entrainment velocity and shell mass ($r = 0.990$) amongst the tested valves. Umbo-away entrainment experiments with all modern valves failed to produce a successful entrainment at the maximum velocity of the open flume, approximately 90cm/s. In an attempt to perform a successful entrainment, a flow
constriction was put in place, blocking off approximately half the diameter of the flume. With a water depth of 16 cm, NDM-5 survived tests with average velocities of 154 cm/s and 169 cm/s without entrainment. At this peak velocity and shell orientation, the smallest shells would slide slowly on the smooth flume bottom, but no other motion could be initiated. Flow visualization experiments showed centimetric areas of separated flow over valves with either orientation, although separation in the umbo-away orientation tended to occur very close to the downstream edge of the valve.

From the velocity profiles, we calculate the velocity as a function of elevation \( z \). The formula for \( u(z) \) near a boundary (Jerolmack et al., 2006) is

\[
    u(z) = \left( u_*/\kappa \right) \ln \left( z/z_o \right)
\]

where \( \kappa \) is von Kármán’s constant, \( u_* \) is the shear velocity (essentially the partial derivative of velocity with respect to \( z \)), and \( z_o \) is a roughness parameter, equal to the elevation at which the extrapolated logarithmic velocity profile goes to zero. By integrating for \( u(z) \), we find a mean velocity for each profile. The bed shear stress \( \tau_b \) is then calculated as

\[
    \tau_b = \rho \ u_*^2
\]

where \( \rho \) is the density of water for the experiment. Since the water in the flume tests was always approximately 1.6° C, the density of water in the experiments was 1000.7 kg/m³. The calculated \( \tau_b \) for the five modern valve ranged from 0.16 kg/ms² to 3.58 kg/ms², increasing exponentially with increased valve mass.
Figure 4. Plot of valve mass against critical bed shear stress for five modern valves in flume entrainment experiments. Equation of the modeling function is $y = e^{-2x^{2.64}}$. 
DISCUSSION

*Mercenaria* and Scaling:

Because *Mercenaria* tend to be thicker and heavier than most bivalve species, it is intuitive in the context of typical solid particles (Hjulstrom, 1939) that it would also require higher velocities of unidirectional flow to move and entrain a *Mercenaria* specimen than valves of smaller, lighter species. When plotting the mass of the tested valves against the flow velocity required for entrainment, we find a strong positive correlation ($r = 0.990$), indicating that as *Mercenaria* grow older (and heavier), they become more difficult to entrain. As mentioned in the *Hydrodynamic Background*, the entrainment of particles is controlled by the relationship between perturbing forces (e.g. lift and drag) and resisting forces (e.g. friction and weight). In the particular case of bivalve shells, lift and drag are controlled by parameters including shape, surface area, and ornamentation. The mass of bivalves may scale differently from the controlling parameters of lift in drag. As bivalve of one species grows larger, it may maintain a similar shape, surface area and ornamentation while thickening and gaining mass. This species would likely become more difficult to entrain with size, as the increased mass provides increased resistance. Alternatively, another species may gain surface area quickly, but remain thin, and thus will entrain more easily with greater size. In most real cases, species gain both mass and surface area as they grow, and the relationship between these scaling parameters will control the relationship between size and ease of entrainment.

The positive correlation between valve mass and entrainment velocity in our empirical experiments demonstrates that for *Mercenaria*, a heavier valve is typically
Figure 5. Linear regression plot of valve mass v. entrainment velocity for flume entrainment experiments done with five modern Mercenaria valves. The equation of the regression line is $y = 0.04x + 60.93$. The correlation is strong ($r = .990$).

Figure 6. Valve mass against projected plan area for fossil Mercenaria valves collected at SMR Aggregates quarry and Dickerson Pit. Fairly strong positive correlation ($r = .835$) indicates that as valves become heavier, they generally gain surface area as well. This allows us to correlate general increase in Mercenaria size to increase in entrainment velocity.
more difficult to entrain. *Mercenaria* is ideal for the comparison of perturbing and resisting forces, because the parameters related to lift and drag are well constrained. As *Mercenaria* range between different sizes, there is little change in ornamentation or shape. Surface area is the lone primary control on lift and drag. Although surface areas of the modern valves used in entrainment experiments were not calculated (due to limited equipment availability), qualitative observations of the modern valves show that the heavier valves in the group also have larger surface areas. This evidence is reinforced by the measurements of the fossil valves, which show a moderately strong positive correlation \((r = 0.835)\) between mass and plan projected plan area. Thus, in the case of *Mercenaria*, the positive correlation between mass and entrainment velocity indicates that as the valves become larger, the added weight tends to have more of an affect on entrainment than the added surface area.

Using the Olivera and Wood (1997) entrainment formula (Eq. 2), the relationship between *Mercenaria* size and behavior can also be analyzed for the fossil specimen. Because mass appears to the first order in the numerator of Equation 2, and \(A_p\) appears to the first order in the denominator, the line of best fit for the plot of weight influence \((I_w = 2W_l)\) against lift influence \((I_l = C_l \rho A)\) demonstrates the scaling relationship between lift and weight forces of the fossil *Mercenaria*. The equation of this line is

\[
l_l = 0.97 l_w + 3.29 \quad (5)
\]

The slope of 0.97 is less than 1, indicating that when these shells are larger, the forces associated with the mass of the valve are larger relative to the forces associated with \(A_p\) than in the case of smaller shells. This would mean a relative rise in entrainment velocity for larger shells, similar to the empirical results. However, because this slope
Figure 7. Valve mass v. calculated entrainment velocity for fossil valves collected in SMR Aggregates Quarry and Dickerson Pit. Calculated velocities were obtained using Equation 2. There is a strong positive correlation between mass and entrainment velocity ($r = 0.817$). The equation of the regression line is $y = 0.0007x + 0.53$.

Figure 8. Plot of the relationship between lift influence and weight influence of entrainment. The slope of 0.97 indicates that as the shells get larger, both the force of lift and force of weight increase, but that the force of weight increases faster relatively, making entrainment more difficult.
is so close to one, the increase in surface area and associated lift does not allow
entrainment velocity to increase very much.

Among the *Mercenaria* collected from the Pinecrest beds, there is much greater
variation in the distribution of mass (m) than in the distribution of projected plan area
\((A_p)\). The mean mass for the shells is \(~232.0\) g, with a standard deviation (StDev) of
\(~78.0\) g. The distribution of projected plan area is much tighter, with a mean of \(~91.5\)
cm\(^2\) and a StDev of \(~16.75\) cm\(^2\). This difference in variation shows that as
*Mercenaria* grow between the sizes included in our collected fossils, they change in
mass more dramatically than they change in surface area.

**Comparison to Other Bivalve Species**

The flume experiments of Olivera and Wood (1997) provide us with
information on the entrainment of 11 other bivalve species, which can be compared to
the entrainment conditions for *Mercenaria*. The design of the Olivera and Wood
(1997) experiments used a similar technique and equipment, but instead of a sheet to
prevent sliding, they placed valves on loose sand, or a fixed grained surface. A
successful entrainment was recorded at the first movement of the valve. For the fixed-
plate experiments, entrainment velocities ranged between 35 cm/s and 74 cm/s. In
comparison, the smallest *Mercenaria* required velocities higher than all but one other
species, while the largest *Mercenaria* required flow velocity over 10cm/s more than
any other species tested. Some of this difference may be due to the more stringent
requirements for entrainment in our tests, although many of the shells in Olivera and
Wood (1997) were entrained by overturning. The comparison of entrainment
velocities found in this study indicates that movement of *Mercenaria* requires slightly higher velocities of unidirectional flow than most bivalve types. However, we also can conclude that the although the masses of our *Mercenaria* specimens are several times that of most disarticulated bivalves, this does not correspond to a similar ratio of entrainment velocities.

**Flow Visualization**

A notable result of our experiments was the contrast in the transportability of *Mercenaria* valves based on the initial orientation of the valves. Our flume tests indicate that a shell with the umbo facing towards the direction of flow is least stable, and when the umbo faces the opposite direction, they are far more difficult to entrain. Even on the slick wooden surface of the flume bottom, high velocities were required to initiate sliding for umbo-away shells. It was difficult to evaluate the advantage in stability of the umbo-away shells because of the limitations of the equipment. Even with the weir removed completely, the flume was incapable of providing shell-level velocities of much more than 90 cm/s, insufficient to entrain the smallest modern valves. By installing a flow constriction in the flume, the flume was able to produce velocities of over 150 cm/s, but was still unable to move any valves in an umbo-away orientation.

Although the umbo-away position presents a more symmetrical profile, it otherwise unclear why this position of the shell was so much more stable in flow. By running flow visualization experiments, we attempted to qualitatively analyze the causes of this difference. Our flow visualization experiments showed centimetric areas of separation for shells in either orientation, and at all tested velocities. There were significant changes in
these fields, dependent on both flow velocity and on the orientation of the tested valve. Vorticies were most pronounced at low velocity, including distinct Kelvin-Helmholtz instabilities in both of the orientations (Figure 9). However, because the highest point in the flow was much farther upstream in the umbo-forward orientation, a larger field of separation over the body of the shell was created (Figure 10). In contrast, the umbo-away orientation has a much shallower upward slope from the upstream edge, and the point of separation is almost directly over the umbo, at the downstream edge of the shell (Figure 11). Unlike the opposite orientation, the separation zone is located over the flume bottom, and not the shell itself. This has two likely effects. Because the separation zone is not over the body, the umbo-away orientation does not create the same drop in pressure over the back of the valve. Secondly, as the separation point is very close to the downstream end of the shell, it is also very close to the point about which the shell pivots in the event of entrainment. This means that the effective lever arm through which the force acts is likely less than half that of the other orientation, greatly reducing the associated torque.

Differences between frontal pressure gradients in the two orientations experiments are not easily seen in flow visualization. The umbo-away profile has a gently sloping upstream profile, in contrast to the tight curvature on the leading edge of a umbo-forward valve. The gentler umbo-away profile likely corresponds to a smaller frontal pressure gradient as well, which would contribute to reduced lift and drag. This in combination with the change in flow separation between orientations accounts for the difference in entrainment velocity.
Figure 9. Kelvin Helmholtz effect over valve NDM-4 in flume. Current is running left to right at approximately 10 cm/s, $Re \approx 10^4$. Note centimeter scale at the far wall, 8 cm behind the center of the valve.
Figure 10. Flow separation over valve NDM-4 with umbo into direction of flow. Velocity $\approx 10$ cm/s at 4 cm above bed, $Re \approx 10^4$. Note separation over the high point of the valve, and circulation back over the ventral edge of the valve, which creates a field of negative pressure on the valve surface. Also note the curvature of the leading edge of the body, and the overhanging surface, a possible source of lift.
Figure 11. Valve NDM-4 in unidirectional flow (right lateral), Velocity \( \approx 10 \text{ cm/s} \) at 4 cm above bed, Reynolds Number \( \approx 10^4 \). Note progression of flow separation vortices over ventral side of the valve. The point of separation is located much farther downstream in this orientation than the Umbo-forward configuration. Gently sloping forward cross-section likely produces low pressure gradients.
CONCLUSIONS AND FUTURE RESEARCH

This study was able to identify several characteristics of the conditions necessary to entrain disarticulated *Mercenaria* valves of different sizes. These observations include the following:

- *Mercenaria* specimens tested, typical of Pliocene sediments in Florida, require entrainment velocities between 68 cm/s and 87 cm/s, dependent on valve mass and surface area.

- As *Mercenaria* specimens grow older and larger, the increase in mass of the valves provides enough resistance to entrainment to counteract lift provided by the increased surface area of the valves. This results in higher entrainment velocities for larger valves than smaller ones. The relationship between entrainment velocity and mass is well approximated by a linear model.

- Critical bed shear stress required to move *Mercenaria* also increases with greater shell mass, but is better modeled by an exponential function.

- In comparison to disarticulated valves of smaller species, *Mercenaria* tend to require similar or slightly higher velocities of unidirectional flow, although they may have several times the mass of other species.

- *Mercenaria* valves oriented with the umbo away from the direction of flow are more stable than in the opposite orientation, a function of lesser pressure gradients over the leading edge of the valve, and reduced effects of flow separation.

Because previous work done on bivalve entrainment is in terms of entrainment velocity and not bed shear stress, we are unable to compare our values for shear stress for those of other species. Still, shear stress is a more useful parameter, as it accounts for
water density, depth and bed roughness, which are otherwise difficult to compare between varying experimental designs. Future experiments on the conditions of bivalve entrainment that investigate the relationship between shell characteristics and bed shear stress would be especially valuable.

To evaluate the uniqueness of finding decimeter-scale *Mercenaria* fossils in concave-up orientations at SMR Aggregates quarry in Sarasota County, FL, systematic sampling should be conducted at this location and other Pliocene shelly sediment outcrops. Information on size distribution and shell orientations at different locations would allow the application of empirical hydrodynamics studies for a better understanding of formation conditions.

**ACKNOWLEDGEMENTS**

This project was made possible by the intellectual and practical contributions of a number of individuals. I would like to thank my advisors at the University of South Florida Paleoenvironments REU, Peter Harries, Rick Oches, Greg Herbert and Roger Portell, for their contribution to the formulation if this research topic, and guidance in fieldwork under the merciless Florida sun. My appreciation is also due to Boris Radosavljevic and Mike Meyer for all sorts of help in data collection and miscellaneous support throughout the project.

The faculty and staff at the St. Anthony Falls Laboratory were unbelievably helpful and accommodating, lending time and expertise to all parts of the experimental phase. Karen Campbell and Doug Jerolmack were particularly excellent in guiding the logistical
and technical aspects of the project. Gratitude is also due to Kate Pound and her children, for providing me with a place to stay during my time at SAFL.

My advisor at Carleton, Clint Cowan, went far beyond the call of duty from the earliest stage of this project. The credit is due to him for making my work at SAFL possible, and even for driving me to and from the laboratory over his winter vacation. His guidance was essential in shaping my work. Finally, I would like to thank the National Science Foundation and Carleton College for generously funding this research, and my fellow majors for support along the way.

REFERENCES CITED:


Geary, D. H., and Allmon, W. D., 1990, Biological and physical contributions to the


Olivera, A. M., 1995, Hydrodynamics of bivalve entrainment and transport, and their implications for paleoenvironment reconstruction: Purdue University, IN 234 p.


Table 1. Data from flume entrainment experiments, including valve characteristics (mass, displacement, density) and entrainment conditions (entries, density, entrainment velocity, standard error, temperature, depth). Standard error refers to the error in entrainment velocity calculations, which were time averaged over a minute at one reading per second.

<table>
<thead>
<tr>
<th>Valve</th>
<th>Mass (g)</th>
<th>Displacement (mL)</th>
<th>Density (g/cm³)</th>
<th>Entrance Velocity (cm/s)</th>
<th>Standard Error (cm/s)</th>
<th>Water Temp. (°C)</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDM-1</td>
<td>412</td>
<td>159</td>
<td>2.591</td>
<td>79.1</td>
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### Table 2a. Measurements of fossil *Mercenaria mercenaria* from SMR Aggregates quarry (SMR), and Dickerson Pit

<table>
<thead>
<tr>
<th>Location</th>
<th>Specimen Length (cm)</th>
<th>Width (cm)</th>
<th>Height (cm)</th>
<th>Proximal Plan Area (cm²)</th>
<th>Frontal Area (cm²)</th>
<th>Proximal Mass (g)</th>
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<tr>
<td>DP-4 #1R</td>
<td>410.9</td>
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<td>4.08</td>
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<tr>
<td>SMR-8-69 GB #2L</td>
<td>204.7</td>
<td>77.01</td>
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<td>9.05</td>
<td>3.04</td>
<td>11.06</td>
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<tr>
<td>11.5</td>
<td>22.39</td>
<td>9.25</td>
<td>3.17</td>
<td>11.55</td>
<td>3.17</td>
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<tr>
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<td>55.8</td>
<td>2.22</td>
<td>8.15</td>
<td>2.83</td>
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<tr>
<td>SMR-8-68 GB #2L</td>
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<td>72.12</td>
<td>3.22</td>
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<td>12.83</td>
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Localities. Area measurements taken using photograph analysis software.
### Table 2b. Measurements of fossil valves continued. Velocity is calculated from Equation 2, using a lift coefficient (C_l) of 0.65, taking from *Saxidomus nuttali*, a bivalve of morphology similar to that of *Mercenaria*. Systematically sampled specimens were found in bulk samples taken at the outcrops, while selected specimens were identified and removed from outcrops individually.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Displacement (ml)</th>
<th>Density (g/cm³)</th>
<th>V (C_l = 0.65)</th>
<th>Thinnest Index</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMR-8-6b GB #2L</td>
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<td>0.722</td>
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<tr>
<td>SMR-8-6b GB #1R</td>
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<td>0.986</td>
<td>1.600</td>
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Selected Specimen:

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<th>V (C_l = 0.65)</th>
<th>Thinnest Index</th>
<th>Elongation</th>
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Systematically Sampled:

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<th>V (C_l = 0.65)</th>
<th>Thinnest Index</th>
<th>Elongation</th>
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<tbody>
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<tr>
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<td>1.600</td>
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<td>0.722</td>
<td>0.74</td>
<td>1.1</td>
</tr>
<tr>
<td>Valve</td>
<td>Height (cm)</td>
<td>VELOCITY PROFILE DATA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td>----------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDM-1</td>
<td>1.3</td>
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<tr>
<td>NDM-5</td>
<td>0.5</td>
<td>72.9 0.5</td>
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<td></td>
</tr>
</tbody>
</table>

Table 3. Velocity (v) profiles for the determination of critical shear stress on each of the valves (NDM-1 through NDM-5) used in flume entrainment experiments. Height refers to the distance above the floor of the flume where the velocity was taken. Velocities are time averaged over a minute at ten readings per second.